THE W51 GIANT MOLECULAR CLOUD

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ABSTRACT

We present 45°–47° angular resolution maps at 50″ sampling of the $^{12}$CO and $^{13}$CO $J = 1–0$ emission toward a 1:39 × 1:33 region in the W51 H II region complex. These data permit the spatial and kinematic separation of several spectral features observed along the line of sight to W51 and establish the presence of a massive ($1.2 \times 10^6 \ M_\odot$), large ($\Delta l \times \Delta b = 83 \times 114$ pc) giant molecular cloud (GMC), defined as the W51 GMC and centered at ($l$, $b$, $V$) $\approx (49^\circ.5, -0^\circ.2, 61$ km s$^{-1}$). A second massive ($1.9 \times 10^5 \ M_\odot$), elongated (22 × 136 pc) molecular cloud is found at velocities of $\sim 68$ km s$^{-1}$ along the southern edge of the W51 GMC. Of the five radio continuum sources that classically define the W51 region, the brightest source at $\lambda 6$ cm (G49.5-0.4) is spatially and kinematically coincident with the W51 GMC and three (G48.9-0.3, G49.1-0.4, and G49.2-0.4) are associated with the 68 km s$^{-1}$ cloud. Published absorption-line spectra indicate that the fifth prominent continuum source (G49.4-0.3) is located behind the W51 molecular cloud. The W51 GMC is among the upper 1% of clouds in the Galactic disk by size and the upper 5%–10% by mass. While the W51 GMC is larger and more massive than any nearby molecular cloud, the average H$_2$ column density is not unusual given its size, and the mean H$_2$ volume density is comparable to that in nearby clouds. The W51 GMC is also similar to other clouds in that most of the molecular mass is contained in a diffuse envelope that is not currently forming massive stars. We speculate that much of the massive star formation activity in this region has resulted from a collision between the 68 km s$^{-1}$ cloud and the W51 GMC.

Key words: ISM: clouds — ISM: general — ISM: individual (W51) — ISM: molecules

1. INTRODUCTION

The compact radio continuum sources comprising W51 (Westerhout 1958) represent one of the most luminous star-forming regions in the disk of the Galaxy (Harper & Low 1971; Hoffman, Frederick, & Emery 1971). The high luminosity, the large number of inferred O-type stars (Bieging 1975), and the location of these sources within a molecular cloud (Mufson & Liszt 1979) all suggest that the W51 region is in the early stages of forming an OB association. Besides the intrinsic interest in the properties of W51, this region represents one of the closest analogs in the disk of the Milky Way to the more vigorous star-forming sites found in other galaxies (e.g., 30 Dor). Since these latter regions are quite distant, W51 affords many advantages in investigating the detailed properties of luminous star-forming sites and inferring how these regions may originate.

One key to understanding the formation and evolution of any star-forming region is establishing the properties of the molecular cloud out of which the stars form. While the molecular gas in the W51 region has been the subject of numerous studies, the interpretation of the results remain controversial. Scoville & Solomon (1973), primarily on the basis of small strip maps in $^{12}$CO(1–0), identified several molecular-line components toward W51 and derived a minimum mass of $10^5 \ M_\odot$ and a diameter of $\sim 20$–30 pc for the molecular cloud that they associated with the most intense radio component at $\lambda 6$ cm (G49.5-0.4; Mehringer 1994). They further suggested that this cloud might be physically related to the several thermal radio continuum sources that make up the W51 H II region complex (Goss & Shaver 1970; Wilson et al. 1970; Georgelin & Georgelin 1976). Subsequent studies of the molecular gas toward W51 have confirmed the existence of a large molecular cloud (Mufson & Liszt 1979; Nakamura et al. 1984; Ohishi et al. 1984; Dame et al. 1987; Solomon et al. 1987; Scoville et al. 1987), although various models continue to be proposed for the relationship of the multiple spectral features seen in the molecular gas lines and their association with the different H II regions.

The primary difficulty in establishing a definitive model of this region is the unique location of W51 in the Galaxy with respect to the Sun. The W51 region has classically been associated with the tangent point of the Sagittarius spiral arm, which is oriented such that the line of sight toward W51 intersects the spiral arm over several kiloparsecs of path length (Shane & Bieger Smith 1966; Burton 1970). Much of the uncertainty surrounding the W51 region stems from establishing whether the numerous radio continuum sources and molecular clouds represent a single, massive star-forming region or the chance projection of unrelated star-forming sites viewed down a spiral arm. To better place the W51 region in context with respect to its location in the Galactic plane, Figure 1 displays the integrated $^{12}$CO(1–0) emission in 10 km s$^{-1}$ velocity bins covering longitudes 40°–55° from the Massachusetts-Stony Brook $^{12}$CO Survey (Sanders et al. 1986). The W51 region is distinguished by bright $^{12}$CO emission extending over a 1° × 1° area centered on ($l$, $b$) $\sim (49^\circ.5, -0^\circ.2$) at velocities of $\geq 55$ km s$^{-1}$. A three-dimensional view of the ($l$, $b$, $V$) $^{12}$CO data cube covering the region surrounding W51 is shown in Figure 2. The $^{12}$CO isointensity contour surface in this figure clearly illustrates both the relatively large number of smaller molecular clouds with typical internal velocity dispersions. 

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of \( \Delta V \sim 3-5 \text{ km s}^{-1} \) and the large concentration of \(^{12}\text{CO} \) emission extending over a \( \sim 20 \text{ km s}^{-1} \) interval in the W51 region. Much of the \(^{12}\text{CO} \) emission in this area has centroid velocities that exceed the maximum velocity permitted by pure circular rotation (i.e., \( V_{\text{max}} \sim 54-57 \text{ km s}^{-1} \); Brand & Blitz 1993). Such velocities have long been noted in 21 cm \( \text{H} \text{I} \) surveys at longitudes near \( l = 50^\circ \) and have been attributed to large-scale streaming motions of gas in a spiral density wave (e.g., Shane & Bieger Smith 1966; Burton 1970).

In principle, the extent and properties of the molecular clouds located in the W51 region can be established by using the kinematic information in the molecular-line data to isolate individual clouds. In practice, previous surveys have had either poor resolution or sparse sampling to make such an attempt feasible. Therefore, we have obtained full-beam–sampled maps of the W51 region in both \(^{12}\text{CO}(1-0) \) and \(^{13}\text{CO}(1-0) \) at subarcminute resolution in order to determine the relationship between the various molecular components. These maps permit us to disentangle the blends of unrelated clouds along the line of sight and to obtain more accurate mass estimates of the molecular gas. These data can also be compared with similar maps of more nearby clouds that have recently been obtained by us and others.

The outline of this paper is as follows: In §2, the observing procedures are described, and channels maps of the \(^{12}\text{CO} \) and \(^{13}\text{CO} \) emission are presented. Analysis of the different spectral features observed in these maps and a more thorough discussion of the main features associated with the compact radio continuum sources in W51 is given in §3. In §4, we discuss the current massive star formation...
2. OBSERVATIONS

2.1. Observing Procedure

A 1°39' × 1°33' region (100 × 96 pixels) toward the W51 region was mapped in \(^{12}\text{CO}(1\rightarrow0)\) (115.271203 GHz) and \(^{13}\text{CO}(1\rightarrow0)\) (110.201370 GHz) in 1995 April using the QUARRY receiver array (Erickson et al. 1992) on the Five College Radio Astronomy Observatory (FCRAO) 14 m telescope. The FWHM beam size of the 14 mm antenna at these frequencies is 45" and 47" at 110 and 115 GHz, respectively. The data were taken in position-switching mode and calibrated with the standard chopper wheel method of observing an ambient temperature load and sky emission. The back ends for each pixel of the array consisted of an autocorrelator spectrometer set to span the velocity range from \(\sim 0-100\ \text{km}\ \text{s}^{-1}\) at 78 kHz sampling (0.20 km s\(^{-1}\) at 115 GHz) and 94 kHz resolution (0.24 km s\(^{-1}\)). During data reduction the spectra were smoothed to a velocity resolution of 0.5 km s\(^{-1}\).

Previous FCRAO measurements indicate that the spillover and scatter efficiency (\(\eta_{\text{sc}}\)) of the telescope and radome is \(\sim 0.7\) at the observed frequencies. The observed antenna temperatures corrected by \(\eta_{\text{sc}}\) are presented as \(T_{B}^{*}\) (Kutner & Ulich 1981). A further correction, the source-coupling efficiency (\(\eta_{\text{s}}\)), accounts for the coupling of the beam to the source. For a uniform source that fills only the main beam of the 14 m telescope, \(\eta_{c}\) is \(\sim 0.7\) (i.e., 30\% of the power is scattered on angular sizes much greater than the FWHM beam size), while for sources with uniform intensity over a diameter of 30', \(\eta_{c}\) is 1.0. In practice, the observed structures in the \(^{12}\text{CO}\) and \(^{13}\text{CO}\) maps span a range of sizes and shapes, and applying a single coupling efficiency for the entire map is incorrect. For simplicity, we present and analyze the data in the temperature scale. The typical \(T_{B}^{*}\) rms noise in the \(^{12}\text{CO}\) and \(^{13}\text{CO}\) maps in 0.5 km s\(^{-1}\) channels is \(0.7\) and 0.6 K, respectively.

2.2. Data

Images of the integrated \(^{12}\text{CO}\) and \(^{13}\text{CO}\) intensity (\(\int T_{B}^{*}\ \text{d}v\)) in 2 km s\(^{-1}\) wide intervals are presented in Figures 3 and 4, respectively, in the velocity range from 40 to 70 km s\(^{-1}\). The values printed in the top left corner of each panel denote the centroid velocity of the particular interval. Extended \(^{12}\text{CO}\) and \(^{13}\text{CO}\) emission was detected between 0 km s\(^{-1}\) and 25 km s\(^{-1}\), but these data are not presented here. This low velocity emission most likely originates from local molecular clouds and is not related to the W51 region of interest here. Little emission was observed between 25 and 35 km s\(^{-1}\) and at velocities in excess of 75 km s\(^{-1}\) (see § 3). Similar velocity structure is also observed in the 21 cm H\(\upalpha\) emission lines (Burton 1970). The following section...
analyzes the velocity structure in the molecular-line maps and identifies individual molecular clouds.

3. ANALYSIS

3.1. Velocity Structure

The $^{12}$CO and $^{13}$CO emission toward the W51 region contains a number of discrete velocity components that overlap in projection both spatially and kinematically. To identify and isolate the emission from these velocity components, multiple Gaussians convolved with the spectrometer channel width were fitted to each spectrum in an automated manner. The free parameters for each Gaussian were the amplitude of the spectral line, the mean velocity, and the line width. The number of Gaussians fitted to each spectrum was determined by searching for contiguous channels that contain an integrated intensity with a signal-to-noise ratio (S/N) of $\geq 3$. Channels containing a local antenna temperature maxima (denoted here as channels $c_i$, $i = 1, n$) in each such section were then identified. A local maximum at channel $c_i$ was deemed a "significant" peak if the antenna temperature in any channel between $c_i$ and the neighboring local maximum at channels $c_{i-1}$ and $c_{i+1}$ decreased by more than 2 $\sigma_{\text{rms}}$ from the antenna temperature at channel $c_i$. The number of significant peaks corresponded to the number of Gaussians fitted to that section.

Each spectrum was smoothed to a velocity resolution of 1.5 km s$^{-1}$ prior to identifying the peaks, although the fits were performed on the 0.5 km s$^{-1}$ resolution data. Spectra with large residuals with respect to the Gaussian fits were visually inspected, and additional Gaussians were added as appropriate. The $^{13}$CO data were easily decomposed into Gaussians in this manner, but it often became difficult to reliably identify the velocity features in the heavily blended
$^{12}$CO lines. Also, toward the compact H$\text{II}$ regions, some of the structure in the $^{12}$CO and $^{13}$CO line profiles can be attributed to the absorption of radiation from hot molecular gas by colder foreground material (see Mufson & Liszt 1979). Away from these compact regions, absorption effects are not as significant, and over most of the cloud, the peaks in the spectral lines should accurately represent the velocity structure along the line of sight.

The results from the Gaussian decomposition of the line profiles are synthesized in Figure 5. The top panel shows histograms of the mean velocities for the $^{12}$CO (heavy lines) and $^{13}$CO (light lines) Gaussians, and the bottom panel shows the total integrated intensity in the Gaussians as a function of the mean velocity. Most of the emission is confined to velocity intervals of 0–25 km s$^{-1}$ and 35–75 km s$^{-1}$. We identify the 0–25 km s$^{-1}$ emission as originating from nearby molecular material and the 35–75 km s$^{-1}$ emission with molecular gas in the Sagittarius spiral arm.

Several velocity components occur repeatedly in both the $^{12}$CO and $^{13}$CO Gaussian fits as signified by the histogram peaks shown in the top panel in Figure 5. In particular, velocity components at 7, 15–25, 44, 49, 53, 60, 63, and 68 km s$^{-1}$ are readily apparent. In terms of the $^{12}$CO and $^{13}$CO integrated intensity, the two major features are the 60 km s$^{-1}$ and 63 km s$^{-1}$ components. A 58 km s$^{-1}$ component is indicated as well since that is the centroid velocity of the molecular-line emission toward the brightest radio continuum source in the W51 region (Mufson & Liszt 1979). Note, however, that the 58 km s$^{-1}$ component is not a prominent feature as judged from Figure 5. The discussion below briefly highlights the morphology of the individual velocity components.

3.1.1. The 7 and 15–25 km s$^{-1}$ Components

The 7 km s$^{-1}$ velocity component contains weak, narrow lines over nearly the entire mapped region and is
undoubtedly a nearby molecular cloud. The 15–25 km s\(^{-1}\) interval appears to contain a few distinct velocity features (see Fig. 5), but it is unclear whether or not these components are physically related.

3.1.2. The 44 km s\(^{-1}\) Component

The 44 km s\(^{-1}\) cloud is elongated parallel to the Galactic plane at \(b = 0^\circ\), although this cloud may form part of a larger structure that extends to lower Galactic latitudes. The molecular gas at these lower latitudes occurs at velocities of ~40 km s\(^{-1}\), which is outside the velocity range assigned to this feature.

3.1.3. The 49 and 53 km s\(^{-1}\) Components

The \(^{12}\)CO emission from the 49 and 53 km s\(^{-1}\) components is more fragmented than the other features mentioned so far. These fragments may represent either individual clouds or the remnants of a once larger cloud in the Galactic plane. The 53 km s\(^{-1}\) cloud is distinguished by bright \(^{12}\)CO emission near \((l, b) \sim (49.4, -0.3)\) that is associated with the compact H\(\text{II}\) region G49.4-0.3 (see § 4.1).

3.1.4. The 58, 60, and 63 km s\(^{-1}\) Components: The W51 Giant Molecular Cloud

The 63 km s\(^{-1}\) component extends for nearly a degree in length and is found mainly in the central and eastern part of the mapped region. This is best observed in the 66 km s\(^{-1}\) panel shown in Figure 3, which represents the line wing emission of this velocity component (as well as emission from the 68 km s\(^{-1}\) cloud discussed below). The 60 km s\(^{-1}\) component consists predominantly of a diffuse patch of emission that extends into a filament to the east and a second filament to the south. The 60 km s\(^{-1}\) and 63 km s\(^{-1}\) velocity components, along with the 68 km s\(^{-1}\) cloud discussed below, likely correspond to the “high-velocity stream” of 21 cm H\(\text{I}\) emission (Burton 1970) that has been attributed to the streaming motions of gas down the Sagittarius spiral arm.

Careful inspection of the channel maps indicates that the spatial distribution of the 60 and 63 km s\(^{-1}\) components generally do not overlap. For example, the western edge of the 63 km s\(^{-1}\) component closely matches the eastern edge of the 60 km s\(^{-1}\) emission. This is best seen in Figure 4 and the 60 and 66 km s\(^{-1}\) velocity panels in Figure 3. Further, the extended emission from the eastern portion of the 63 km s\(^{-1}\) component is just above the filamentary extension of the 60 km s\(^{-1}\) component. Such interfaces are unlikely to occur by chance from two unrelated clouds along the line of sight and suggest that the 60 and 63 km s\(^{-1}\) components represent kinematic structure within a single molecular cloud. Velocity differences of this magnitude are commonly observed in nearby molecular clouds (e.g., Bally et al. 1987).

The 58 km s\(^{-1}\) component is dominated by bright, compact molecular emission and does not contain the diffuse extended emission that characterizes the 60 and 63 km s\(^{-1}\) features. Inspection of the channel maps suggests that this velocity component also reflects the interval kinematic structure within a single cloud encompassing the 60 and 63 km s\(^{-1}\) clouds. For example, the emission from the filament protruding to the southern portion of the mapped region contains primarily a centroid velocity of 58 km s\(^{-1}\) closest to bright compact \(^{12}\)CO and \(^{13}\)CO emission. Further away from this bright, compact emission region, the velocity of the filament changes to ~60 km s\(^{-1}\). Similar velocity patterns are observed in emission features along the eastern and western edges of the map. These results suggest that the emission constituting the 58, 60, and 63 km s\(^{-1}\) components represent the internal velocity structure within a single molecular cloud. Koo (1997) reached similar conclusions concerning the atomic hydrogen clouds at these velocities based upon H\(\text{I}\) absorption observations toward the radio continuum sources. Since the bright \(^{12}\)CO emission associated with the 58 and 60 km s\(^{-1}\) components are coincident with the brightest radio continuum source in the W51 region (G49.5-0.5; see § 4.1), we henceforth refer to the 58-60-63 km s\(^{-1}\) components as the W51 molecular cloud.

3.1.5. The 68 km s\(^{-1}\) Component

The 68 km s\(^{-1}\) component extends for ~1° east-west across the image and also likely constitutes part of the “high-velocity stream” identified in H\(\text{I}\) surveys (Burton 1970). Interestingly, the 68 km s\(^{-1}\) filament is located at the southern edge of the diffuse emission associated with the W51 molecular cloud at velocities \(\gtrsim 63\) km s\(^{-1}\) (see Figs. 3 and 4). Again, such a clear truncation of the W51 molecular cloud at the location of the 68 km s\(^{-1}\) cloud is unlikely to occur from two random clouds along the line of sight and strongly suggests that these two clouds are physically related objects at a common distance. Nonetheless, the elongated appearance of the 68 km s\(^{-1}\) cloud is in stark contrast to the roughly circular shape of the W51 cloud, indicating that these two objects are best treated as individual structures rather than a single molecular cloud.

3.2. Properties of the W51 and the 68 km s\(^{-1}\) Molecular Clouds

The physical properties of the molecular clouds in the W51 region can be determined from the Gaussian decomposition of the line profiles. We single out these two clouds
since they contain four of the five bright H II regions found in radio continuum surveys (see § 4.1). In deriving the properties, the distance to the W51 cloud is assumed to be 7.0 ± 1.5 kpc as determined from proper-motion studies of the W51 Main H$_2$O maser in the G49.5-0.4 dense core (Genzel et al. 1981). The 68 km s\(^{-1}\) cloud was assumed to have the same distance based on its apparent association with the W51 cloud as discussed above. The other clouds are not included in this analysis since their distances are unknown.

The properties of the W51 and 68 km s\(^{-1}\) clouds are summarized in Table 1. The cloud size represents a visual estimate of the extent of the detectable $^{12}$CO emission along the major ($\theta_{\text{max}}$) and minor ($\theta_{\text{min}}$) axis of the cloud. The cloud line width, $\Delta V_{\text{FWHM}}$, is the FWHM of the sum of the Gaussian fits making up the respective clouds. Two estimates of the cloud mass are provided in Table 1. The virial mass, $M_{\text{vir}}$, was calculated using the expression $M_{\text{vir}} = 209 R \Delta V^2$, where $\Delta V$ is the FWHM line width in km s\(^{-1}\) and $R$ is the cloud radius [$D_{97} \theta_{\text{max}} \theta_{\text{min}}^{1/2}/2.0$] in parsecs at the zero intensity level. While the cloud size is actually measured at a finite $^{12}$CO intensity level, we find it unlikely that the clouds are appreciably larger at lower intensities, and no correction to the observed cloud size was applied. Note that the above expression for the virial mass is appropriate for a uniform-density spherical cloud. The equivalent expression for an $r^{-1}$ and $r^{-2}$ density cloud would decrease the constant factor in the virial mass expression to 188 and 125, respectively.

A second mass estimate can, in principal, be obtained from the $^{12}$CO and $^{13}$CO data using the LTE analysis (Dickman 1978). However, in blended regions, it is often difficult to associate $^{12}$CO Gaussian fits with analogous $^{13}$CO features. Therefore, the H$_2$ column densities were estimated by applying a constant conversion factor to the $^{12}$CO integrated intensities (Dickman 1975; Solomon et al. 1987; Strong et al. 1988). To ensure that the Galactic conversion factor is indeed valid for the W51 region, the conversion factor was estimated from lines of sight with unblended $^{12}$CO and $^{13}$CO lines in the 56–71 km s\(^{-1}\) velocity interval that defines the W51 and 68 km s\(^{-1}\) clouds. The H$_2$ column densities for these lines of sight were estimated using the procedure outlined by Dickman (1978) and assuming a $^{13}$CO/H$_2$ abundance of $1.5 \times 10^{-6}$. A histogram of the ratio of the H$_2$ column densities to $^{12}$CO-integrated intensities is strongly peaked with a mean value of $1.7 \times 10^{20}$ cm\(^{-2}\) (K km s\(^{-1}\)) and is similar to the conversion factor that has been derived for the Galaxy [$(2.3) \times 10^{20}$ cm\(^{-2}\) (K km s\(^{-1}\))-1; Strong et al. 1988 and references therein]. The masses ($M_{\text{CO}}$) computed from the $^{12}$CO integrated intensities were calculated by adopting the conversion factor derived from the W51 data and include a multiplicative factor of 1.36 to incorporate the mass contribution from heavier elements.

The results summarized in Table 1 indicate that the W51 molecular cloud has a mean diameter of ~97 pc and a mass\(^2\) of ~$10^6$ $M_\odot$. The similarity in the two mass estimates indicates the gravitational potential energy is approximately equal to the kinetic energy and that self-gravity must play a critical role in the evolution of the W51 molecular cloud. The 68 km s\(^{-1}\) cloud is 136 pc in length but only 22 pc wide over most of the minor axis. Such an obvious departure from spherical symmetry renders the virial mass estimate suspect, and so the mass of the 68 km s\(^{-1}\) cloud was estimated only using the $^{12}$CO conversion factor. The mass obtained, ~$10^5$ $M_\odot$, is an order of magnitude less than that of the W51 cloud.

A comparison of the W51 cloud properties with the size and mass spectrum of molecular clouds in the Galaxy (e.g., Sanders, Scoville, & Solomon 1985; Solomon et al. 1987) shows that the W51 molecular cloud is one of the largest GMCs in the Galactic disk. Among the ~5000 molecular clouds with diameters in excess of ~22 pc (and corresponding masses ~$10^5$ $M_\odot$; i.e., GMCs), the W51 GMC is in the top 1% of the clouds by size and the upper 5%–10% by mass. For the 68 km s\(^{-1}\) cloud, although its mass is typical of a relatively low-mass GMC, a distinguishing feature is its shape. The ratio of the major to minor axis of the 68 km s\(^{-1}\) cloud is ~6. In the cloud catalog by Solomon et al. (1987), 85% of the clouds have an aspect ratio less than 2, and only one object has an aspect ratio greater than observed for the 68 km s\(^{-1}\) cloud. Clearly an elongated shape over such a large length scale is unusual in the molecular interstellar material and may indicate that the 68 km s\(^{-1}\) cloud is a transient structure originating from a relatively recent dynamical event.

4. DISCUSSION

4.1. Massive Star Formation in the W51 Region

Now that the individual molecular clouds in the W51 region have been identified, their relationship to the massive star-forming sites can be explored. Three images of the W51 region are shown in Figure 6: a map of the integrated $^{12}$CO (1–0) intensity generated from Gaussian fits with mean velocities between 56 and 71 km s\(^{-1}\) (i.e., the W51 and 68 km s\(^{-1}\) clouds), an image of the 60 $\mu$m emission from the IRAS Sky Survey Atlas, and a J21 cm radio continuum image (Koo & Moon 1997). The bulk of the 60 $\mu$m emission is elongated parallel to, but slightly below, the galactic plane, and is coincident with bright radio continuum emission. Of the sources labeled in the J21 cm continuum map, W51C has predominantly a nonthermal continuum spectrum and is thought to be a supernova remnant (Subrahmanyan & Goss 1995), while the other sources have thermal spectra and are compact H II regions. The radio continuum sources G49.4-0.3 and G49.5-0.4 are classically referred to as W51A (Kundu & Velusamy 1967), with the G49.5-0.4 region containing the infrared source W51 IRS 1 (Wynn-Williams, Becklin, & Neugebauer 1974) and the H$_2$O masers W51 North, W51 South, and W51 MAIN (Genzel & Downes 1977). Sources G48.9-0.3, G49.1-0.4, and

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TABLE 1

<table>
<thead>
<tr>
<th>Cloud</th>
<th>$\theta_{\text{min}} \times \theta_{\text{max}}$ (pc x pc)</th>
<th>$\Delta V_{\text{FWHM}}$ (km s(^{-1}))</th>
<th>$M_{\text{CO}}$ ($10^5$ $M_\odot$)</th>
<th>$M_{\text{vir}}$ ($10^5$ $M_\odot$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>W51</td>
<td>83 x 114</td>
<td>8.9</td>
<td>11.9</td>
<td>8.2</td>
</tr>
<tr>
<td>68 km s(^{-1})</td>
<td>22 x 136</td>
<td>4.6</td>
<td>1.9</td>
<td>...</td>
</tr>
</tbody>
</table>

* Assumed distance is 7.0 kpc (Genzel et al. 1981).

$^a$ FWHM of the sum of the $^{12}$CO(1–0) Gaussian fits.

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$^2$ The virial mass derived here agrees well with that estimated by Dame et al. (1987), but is a factor of 4 less than that found by Solomon et al. (1987). Solomon et al. (1987) derived a substantially larger velocity dispersion, and hence computed a larger virial mass, most likely by including the emission from the 68 km s\(^{-1}\) cloud and several other velocity components that we did not associate with the W51 molecular cloud.
G49.2-0.4 are collectively known as W51 B (Kundu & Velusamy 1967). The observed radio continuum fluxes (Koo 1997) and far-infrared luminosities (~10^6–7 L_{\odot}; Rengarajan et al. 1984; Harvey et al. 1986) imply the presence of one or more O stars in each of these regions.

Figure 6 shows that many of the radio continuum sources have corresponding peaks in the molecular-line and far-infrared images. In addition to the spatial coincidences, these radio continuum sources have recombination line velocities (Wilson et al. 1970) similar to the velocity components identified from the 12CO observations. The G49.5-0.4 H II region has a recombination line velocity of 59 km s^{-1} and is spatially coincident with the strong 12CO emission associated with the W51 molecular cloud. The recombination line velocities toward G48.9-0.3, G49.1-0.4, and G49.2-0.4 are 66, 72, and 66 km s^{-1}, respectively, and are located along the 68 km s^{-1} molecular cloud. Finally, the G49.4-0.3 H II region has a recombination line velocity of 53 km s^{-1} and is coincident with the bright 12CO and 13CO emission from the 53 km s^{-1} molecular cloud (note that the molecular gas associated with this H II region is outside the velocity range that defines the W51 GMC). H I (Koo 1997 and H_2CO (Arnal & Goss 1985) spectra toward this source exhibit absorption features at velocities of 63–65 km s^{-1}, indicating that G49.4-0.3 must be located behind the W51 GMC. However, these observations do not indicate whether this source is situated just beyond W51 and hence is physically related to the H II region complex or if it is a distant, unrelated background massive star-forming site. The molecular-line maps presented here provide no compelling reason for (or against) such an association.

To search for any additional massive star-forming sites in the W51 molecular cloud, the IRAS Point Source Catalog, vers. 2, was examined for objects that have at least two “high”-quality detections among the four IRAS bands and a rising spectral energy distribution toward longer wavelengths. These criteria were designed to select a reliable sample of objects with far-infrared colors characteristic of embedded star-forming regions (Walker et al. 1989). Of the 40 IRAS point sources within the mapped region that meet these criteria, the seven brightest objects at 25 μm are located along the interface between the W51 and the 68 km s^{-1} clouds. Visual inspection of IRAS 60 μm image in Figure 6 confirms that the brightest sources are located along this ridge. Assuming that the other point sources are located at the distance of the W51 molecular cloud (although many of them are almost certainly foreground objects), point sources found away from this interface have far-infrared luminosities in the four IRAS bands less than 40,000 L_{\odot} and inferred spectral types later than the zero-age main sequence B0.5 (Vacca, Garmany, & Shull 1996). Thus embedded O-type stars in the W51 region currently are confined to the southern extreme of the molecular cloud.

4.2. Comparison with Other Molecular Clouds

The extreme star formation characteristics of the W51 region raises the question as to whether the star formation activity stems from unusual global properties in the W51 molecular cloud or from unusual conditions found that are local to the massive star-forming sites. These possibilities can be explored by comparing the W51 cloud properties with other star-forming regions that have also been extensively mapped in 12CO and 13CO. In particular, we shall compare the W51 and 68 km s^{-1} clouds with the molecular clouds associated with the H II regions Sh 140, 155, 235, 247, 252, and 255, which have been mapped with the same receiver and telescope used for the W51 observations (Heyer, Carpenter, & Ladd 1996; Carpenter, Snell, & Schloerb 1995). The embedded high-mass stellar content in this comparison sample is generally limited to a single early B/late O–type star and is in stark contrast to the cluster of O stars forming in the W51 molecular cloud.

The clouds in the comparison sample have diameters of ~20–55 pc and masses of (~2 × 10^4)–(7 × 10^4) M_{\odot}. Thus, the W51 molecular cloud is ~2.5 times larger and ~10 times more massive than these objects. Note that the molecular clouds associated with Sh 247, 252, and 255 are distinct regions within the Gem OB1 cloud complex, which has a total mass of 3 × 10^5 M_{\odot} and a diameter of ~150 pc.
(Carpenter, Snell, & Schloerb 1995). While the spatial size of the Gem OB1 complex is larger than the W51 cloud, the W51 cloud exhibits a continuous structure \( \sim 100 \) pc in size, as opposed to the fragmentary appearance of the Gem OB1 complex. The 68 km s\(^{-1}\) cloud is also more massive than the objects in the comparison sample and is significantly more elongated than any of the clouds considered here. Thus the W51 and 68 km s\(^{-1}\) clouds are at the extreme in terms of cloud masses and sizes compared with objects in this sample. With the possible exception of the 68 km s\(^{-1}\) cloud, these clouds are similar, though, in that they appear to be gravitationally bound.

The size and mass of a cloud are not necessarily the key parameters that control the star formation activity within the cloud. Intuitively, one might expect that the amount of matter above a critical density to be the critical variable for otherwise similar clouds. Thus if the massive star formation activity in W51 has resulted from the large-scale collapse of the cloud, one would expect the volume and column density to be larger than found in a typical cloud. As an indirect measure of the \( \text{H}_2 \) column densities, Figure 7 shows histograms of the observed \(^{13}\text{CO}\) integrated intensities for each of the clouds in our sample. The lowest integrated intensity shown for any cloud is 3 K km s\(^{-1}\) since that is approximately the highest 3 \( \sigma \) detection limit among the various \(^{13}\text{CO}\) surveys. Comparison of the \(^{12}\text{CO}\) and \(^{13}\text{CO}\) intensities suggests that the \(^{13}\text{CO}\) emission is optically thin if the \(^{12}\text{CO}\) and \(^{13}\text{CO}\) excitation temperatures are equal as assumed in the LTE analysis (see Dickman 1978). Therefore, the distribution of \(^{13}\text{CO}\) integrated intensities should accurately trace the \( \text{H}_2 \) column density distributions as long as the \(^{13}\text{CO}\) abundance is roughly constant within a cloud. The \(^{13}\text{CO}\) integrated intensities in Figure 7 can be converted to \( \text{H}_2 \) column densities for an assumed \(^{13}\text{CO}/\text{H}_2\) abundance of \( 1.5 \times 10^{-6} \) (Bachiller & Cernicharo 1986) with the formula

\[
N(\text{H}_2) = 3.05 \times 10^{19} T_{\text{ex}} e^{5.29/T_{\text{ex}}} \int T_{\text{A}(^{13}\text{CO})} dv \text{ cm}^{-2}.
\]

For an excitation temperature of \( T_{\text{ex}} = 10 \) K, the 3 K km s\(^{-1}\) integrated intensity limit imposed for Figure 7 corresponds to an \( \text{H}_2 \) column density of \( 1.5 \times 10^{21} \) cm\(^{-2}\), or an visual extinction of \( \sim 1^\circ.5 \) (Bohlin, Savage, & Drake 1978). Variations in the \(^{13}\text{CO}\) abundance and excitation conditions will obviously effect the absolute conversion from \(^{13}\text{CO}\) integrated intensities to \( \text{H}_2 \) column densities, and the comparisons here are intended to search for large differences (factors of several or more) in the typical column densities in these clouds.

Figure 7 shows that the distributions of \(^{13}\text{CO}\) integrated intensities peak near the detection limit of 3 K km s\(^{-1}\) for each cloud, with a long tail toward the higher integrated intensities. The tail of these distributions correspond to the high column density regions and are often associated with star-forming sites. The mean \(^{13}\text{CO}\)-integrated intensity among the clouds varies between 4.9 and 9.7 K km s\(^{-1}\), with the W51 cloud containing the third highest mean intensity, and the 68 km s\(^{-1}\) cloud, the highest. The high values found for the 68 km s\(^{-1}\) cloud may be a result of an unusual viewing angle, as either this cloud is a sheet of gas observed edge-on or a long, narrow filament. These results imply that most of the mass in each cloud is contained in lines of sight with column densities corresponding to less than a few magnitudes of visual extinction. Thus the W51 GMC is similar to other clouds in that the diffuse envelope contains more mass than the high column density cores.

While the W51 cloud contains a higher column density on average than the other clouds, this can be attributed to the fact that it is more than twice as large as some clouds in the sample. Indeed, assuming that the 1.2 \( \times 10^6 \) \( M_\odot \) W51 cloud is distributed in a sphere of diameter of 97 pc (see Table 1), the average \( \text{H}_2 \) volume density is 40 cm\(^{-3}\), comparable to the volume density inferred in nearby molecular clouds (Blitz 1991; Carpenter, Snell, & Schloerb 1995). This suggests that the entire W51 molecular is probably not in an advanced stage of collapse, and that the intense star formation activity in W51 likely results from forces acting on a localized region. In retrospect, this is perhaps not surprising given that the massive star-forming regions in W51 are located at the edge of the cloud and not in the center as expected if, for example, the entire cloud was systematically collapsing.

Contrary to the global properties, the gas properties local to the W51 massive star-forming regions do appear to be unusual compared with the molecular clouds in the solar neighborhood. Submillimeter continuum observations have shown that the core containing the G49.5-0.4 H\( \Pi \) region contains \( \sim 10^5 \) \( M_\odot \) of gas with a mean \( \text{H}_2 \) volume density of \( \sim 5 \times 10^4 \) cm\(^{-3}\) over a 3 pc radius region (Sievers et al. 1991). By contrast, submillimeter observations indicate that the most massive cores in nearby molecular clouds typically have masses \( \sim 2-3 \) orders of magnitude less than that of the G49.5-0.4 core (e.g., Oldham et al. 1994; Mezger et al. 1992; Schloerb, Snell, & Schwartz 1987; Jaffe et al. 1984). While the G49.5-0.4 core does not necessarily contain higher gas densities, it does contain more gas at the densities needed to form stars.

4.3. Evolution of the W51 Molecular Cloud

The above discussion suggests that the key to understanding the massive star formation activity in the W51 complex is determining the forces that acted on a localized region within the cloud. The molecular-line maps presented here allow us to speculate on what these forces may be. As shown in Figures 3 and 4, the diffuse emission from the W51 GMC truncates at the location of the 68 km s\(^{-1}\) cloud for velocities \( \geq 63 \) km s\(^{-1}\). This morphology was used in § 3 to argue that the W51 and 68 km s\(^{-1}\) clouds are at a common distance since such an interface is unlikely to result from the chance superposition of unrelated molecular clouds. One way such an interface could form is if the 68 km s\(^{-1}\) cloud has collided into the W51 GMC (see also Arnal & Goss 1985; Pankonin, Payne, & Terzian 1979). Molecular gas does extend below the 68 km s\(^{-1}\) cloud at lower velocities, however. In this picture, given the three-dimensional structure of the W51 GMC, this material has not crossed the path of the 68 km s\(^{-1}\) cloud. Both \(^{12}\text{CO}\) and \(^{13}\text{CO}\) spectra toward the G49.5-0.4 H\( \Pi \) region (Koo 1997; Arnal & Goss 1985; Mufson & Liszt 1979) contain absorption lines at velocities \( \geq 65 \) km s\(^{-1}\), and relative to the line of sight, the 68 km s\(^{-1}\) cloud must be located in front of the W51 GMC. Since the velocity difference between the two clouds (at least 5 km s\(^{-1}\)) is larger than the sound speed, a shock front will form that will compress the molecular gas and possibly induce star formation (Elmegreen \\& Elmegreen 1978).

The qualitative model of two colliding clouds accounts for several properties of the W51 region. First, one would expect that star formation should occur preferentially along
the interface region. The IRAS image in Figure 6 shows that this is indeed the case for massive stars, as the northern half of the W51 GMC appears devoid of embedded O-type stars despite containing most of the cloud mass. The cloud collision model would also suggest that the massive star-forming regions along the collision interface should have a common age. While the ages of these stars are not known, the lifetime of the mid-O-type stars found in the W51 region (Mehringer 1994; see also Koo 1997) places an upper limit to the stellar ages of ~5 Myr (Meynet et al. 1994). The actual ages may be considerably less since these O stars are still in the compact H II region phase, which has a lifetime of less than 1 Myr (Churchwell 1990; Comerón & Torra 1996). Further support for a cloud-cloud collision model comes from considering the projected distance (73 pc) between the two furthest separated star-forming regions along the W51/68 km s$^{-1}$ cloud interface. The sound-travel time across this distance is nearly 2 orders of magnitude larger than the O star lifetime. Therefore, these star-forming regions must have been created by either a single event operating along the entire northern edge of the cloud or from up to 4 separate, but nearly simultaneous, events. Given the scarcity of embedded O stars in the Galaxy, the cloud-collision model would provide a natural explanation for simultaneous star formation along the ridge. Ultimately, the suggested collision between the W51 and 68 km s$^{-1}$ clouds may be related to a spiral density wave. The anomalous gas velocities in the W51 region have long been attributed to streaming motions in the Sagittarius spiral arm (Shane & Bieger-Smith 1966; Burton 1970). The associated spiral density wave may have indirectly led to the massive star formation activity in the W51 region by enhancing the number density of clouds and increasing the probability of a cloud-cloud collision. Furthermore, a spiral-wave shock, if present (see Lubow, Balbus, & Cowie 1986), and flatten any clouds Indeed, such a shock could account for the highly elongated shape of the 68 km s$^{-1}$ cloud. The W51 GMC, however, remains roughly circular in shape, and globally its evolution is likely still dominated by self-gravity.

Finally, we briefly consider the implications of these results for other star-forming regions. While the W51 star-forming region exceeds all nearby embedded star-forming sites in terms of the number of O stars, bolometric luminosity, and dense core mass, W51 itself is dwarfed by some star-forming regions in nearby galaxies. Most notably, the 30 Dor region in the Large Magellanic Cloud contains an order magnitude more O stars than W51 (Vacca et al. 1995).
At larger distances, many interacting galaxies contain even yet more vigorous massive star-forming regions that may be dense enough to represent young globular clusters (Whitmore et al. 1993). Most of the molecular gas appears to have been dispersed in these clusters already, and in any event, the distances to these systems precludes any detailed studies of the natal clouds. The most significant piece of information afforded by the W51 molecular maps is that despite containing one of the most massive dense cores known in our Galaxy, most of the mass in the W51 molecular cloud is not currently forming massive stars. Thus, it is easy to imagine that the increase in the number of cloud-cloud collisions that presumably results in interacting galaxies may lead to a larger number of star-forming regions throughout a single cloud or more intense star formation activity within a small region. In fact, the mass within the W51 molecular cloud is comparable to that in globular clusters, and it may not require the conglomeration of many giant molecular clouds to form these stellar systems, but the large-scale collapse of a single GMC.

5. SUMMARY

We have mapped a 1.39 × 1.33 region toward the W51 H II region complex at 45°–47° resolution and 50' sampling in the J = 1–0 transitions of 12CO and 13CO. From these data we have identified the major molecular clouds and have associated these clouds with the massive embedded star-forming sites in the W51 region. We find that:

1. The two most prominent clouds in the W51 region are the 58–60–63 km s \(^{-1}\) cloud (defined as the W51 GMC) and the 68 km s \(^{-1}\) cloud. The W51 GMC is associated with the brightest 6 cm continuum source in W51 (G49.5-0.4), and the 68 km s \(^{-1}\) cloud contains the H II regions G49.8-0.3, G49.1-0.4, and G49.2-0.4. Published absorption-line spectra (Koo 1997; Arnal & Goss 1985) indicate that the fifth brightest H II region in the area, G49.4-0.3, must be located behind the W51 GMC, but it remains unclear whether or not it is physically associated with the other star-forming regions.

2. The mass of the W51 GMC and the 68 km s \(^{-1}\) clouds are ~1.2 × 10\(^{6}\) \(M_\odot\) and 1.9 × 10\(^{5}\) \(M_\odot\), respectively. The W51 molecular cloud is roughly circular in shape with a mean diameter of ~97 pc and appears to be gravitationally bound. Compared with the ~5000 GMCs in the Galactic disk, W51 is among the top 1% by size and the top 5%–10% in terms of cloud mass. The 68 km s \(^{-1}\) cloud is an elongated filament of ~136 pc × 22 pc in size. The 6:1 aspect ratio of the major and minor axes in the 68 km s \(^{-1}\) cloud is rare in the Galaxy over such a large size scale (Solomon et al. 1987) and suggests that this molecular cloud may represent a transient feature.

3. The properties of the W51 and 68 km s \(^{-1}\) clouds are compared with nearby clouds that have been studied in a similar manner but contain lower levels of massive star formation activity. While the W51 cloud is larger and more massive than nearby clouds, the mean H\(_\alpha\) column density is not unusual given the large size, and the mean H\(_\alpha\) volume density is comparable. The W51 GMC is similar to other clouds in that most of the molecular mass is contained in a diffuse molecular envelope that is not forming massive stars. The 68 km s \(^{-1}\) cloud contains the largest mean column density among the clouds studied here, but this may be a result of an unusual viewing angle for this elongated cloud. We suggest that much of the star formation activity in the W51 region has not resulted from global collapse of the W51 cloud but from forces acting on localized regions within the cloud.

4. We speculate that much of the massive star formation activity in W51 has resulted from a collision between the W51 and 68 km s \(^{-1}\) molecular clouds. This conjecture can explain the string of embedded O stars that are spread out for 70 pc along the interface between the W51-68 km s \(^{-1}\) clouds and why massive star formation is currently confined to the southern ridge of the W51 GMC.

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