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Steven N. Shore

Indiana University - South Bend

Loris Magnani

University of Georgia

Ted La Rosa

Kennesaw State University, tlarosa1@kennesaw.edu

Meredith N. McCarthy

University of Georgia

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MECHANISMS FOR THE ORIGIN OF TURBULENCE IN NON-STAR-FORMING CLOUDS: THE TRANSLUCENT CLOUD MBM 40

STEVEN N. SHORE

Department of Physics and Astronomy, Indiana University–South Bend, 1700 Mishawaka Avenue, South Bend, IN 46634-7111;
 and Dipartimento di Fisica “ Enrico Fermi,” Università di Pisa, 56100 Pisa, Italy; sshore@iusb.edu

LORIS MAGNANI

Department of Physics and Astronomy, University of Georgia, Athens, GA 30602; loris@milan.physast.uga.edu

T. N. LAROSA

Department of Biological and Physical Sciences, Kennesaw State University, 1000 Chastain Road, Kennesaw, GA 30144;
 ted@avatar.kennesaw.edu

AND

MEREDITH N. MCCARTHY

Department of Physics and Astronomy, University of Georgia, Athens, GA 30602; ampheres@arches.uga.edu

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ABSTRACT

We present a multiline, high spatial and velocity resolution CO, H I, and *IRAS* 100 μm study of the high-latitude, low-mass, non-star-forming, translucent molecular cloud MBM 40. The cloud mass is distributed into two ridges, or filaments, that form a hairpin structure. Velocity channel maps indicate a highly ordered flow in the molecular gas, with the northeastern part of the filament moving away from and the southwestern filament moving toward the observer relative to the mean cloud radial velocity. Significant changes in emissivity occur over 0.03 pc, indicating large transverse density gradients along the ridges. However, the velocity field appears to be continuous, showing no evidence for shock compression. The neutral hydrogen at the same velocity envelops the molecular gas but shows a decrease along the hairpin, indicating that the atomic hydrogen has converted to H₂; the strongest 100 μm emission coincides with the CO, not the H I, emission peak. These results indicate that MBM 40 is condensing out of a larger scale flow and is structured by thermal instability and shear flow turbulence. This externally driven turbulence does not produce large compression and may explain why gravitational collapse and star formation do not occur in MBM 40.

Subject headings: ISM: clouds — ISM: molecules — radio lines: ISM — turbulence

On-line material: color figures

1. INTRODUCTION

The high-latitude translucent molecular clouds are ideal sites for studying turbulence in the local interstellar medium. They are dynamically and morphologically much simpler than star-forming clouds, in most cases lacking complications introduced by self-gravity, active collapse, and energy injection from star formation (see, e.g., Magnani et al. 1995; Caillaud, Magnani, & Fryer 1995; Hearty et al. 1999). Consequently, without internal sources to power the flows, their observed inhomogeneous structure and nonthermal velocity fields must reflect larger scale physical processes at work in the surrounding interstellar medium. These include shock compression resulting from collisions of turbulent gas streams and large-scale turbulent shear flows acting in concert with fluid, MHD, and thermal instability.

In earlier studies using velocity autocorrelation and line profile statistics (Magnani, LaRosa, & Shore 1993, hereafter MLS93; LaRosa, Shore, & Magnani 1999, hereafter LSM99), we found evidence for transient coherent structures in the translucent cloud MBM 16. According to Hussain (1983), a coherent structure is “a connected turbulent fluid element with instantaneously phase-correlated vorticity over its spatial extent;” they are the nonrandom, persistent structures (e.g., vortex tubes, spanwise rolls) that arise (Hussain 1983, 1986; Shore 1992; Holmes, Lumley, & Berkooz 1996; Grossman 2000) in laboratory and environmental shear flows. We therefore postulated that an *external*

shear flow powers the turbulent velocity field in MBM 16. Given that turbulence in the interstellar medium rapidly decays (see, e.g., Mac Low 1999; Padoan & Norlund 1999), shear flows provide a new, robust source for maintaining the turbulence in non-star-forming clouds.

In order to test the generality of this result we have undertaken a detailed study of another translucent cloud, MBM 40. This is a lower mass, more compact cloud that is much closer to virial (dynamical) equilibrium than MBM 16 (see Magnani et al. 1996). It is embedded in a cirrus complex at a distance of about 120 pc (Penprase 1993). Magnani et al. (1996) combined the *IRAS* images of MBM 40 with very limited spatial coverage in a number of molecular species (¹²CO, ¹³CO, CS, and H₂CO). They established some basic properties of the cloud: a mass of 20–40 $M_{\odot}$, a mass for just the molecular ridge of about 20 $M_{\odot}$, the presence of dense substructures with $n_{\text{H}_2} \geq 10^3 \text{ cm}^{-3}$, and H₂ column densities of $N_{\text{H}_2} = (1\text{--}7) \times 10^{20} \text{ cm}^{-2}$. Similar physical properties were obtained by van Dishoeck et al. (1991) using multiple CO transitions and several chemical tracers observed at four points within the denser part of the cloud. They found gas temperatures of $\sim 30 \text{ K}$, volume number densities of $\sim 10^3 \text{ cm}^{-3}$, and H₂ column densities of $(5\text{--}8) \times 10^{20} \text{ cm}^{-2}$.¹

¹ Two of our pointings overlap theirs, locations 40B and 40C in their Table 1. They find OH, H₂CO, and C₃H₂ in field 40B, which corresponds to the most intense emission, as well as to the reference point during our mapping. This location, consequently, seems to be a density enhancement and not simply a superposition of dynamically unrelated regions.

Magnani et al. (1996) argued that unlike most other high-latitude translucent clouds, MBM 40 is on the margin of being gravitationally bound. Yet despite this, they found no indication of internal star formation. We return to this point below. Following our initial submission of this paper, we became aware of a recent publication by Lee, Chung, & Kim (2002). They mapped MBM 40 in ^{12}CO (1–0) and ^{13}CO (1–0) using the 14 m radio telescope at Taeduk Radio Astronomy Observatory. Although their map is under-sampled, their results are confirmed and extended by ours. In particular, our fully sampled H I and multitransition CO maps allow us to address the origin and distribution of the turbulence in this cloud.

2. OBSERVATIONS

The ^{12}CO (1–0) data were obtained with the 14 m radio telescope of the Five Colleges Radio Astronomy Observatory (FCRAO) in 2000 March and April.² At 115 GHz, the beamwidth is $45''$, which corresponds to a size scale of 0.026 pc at 120 pc, the nominal cloud distance that we adopt for the remainder of the paper. We mapped the cloud with the SEQUOIA focal plane array, which then consisted of 16 single-polarization receivers arranged in a 4×4 pattern so that 16 locations on the sky can be observed simultaneously. The 4×4 grid extends over a 5.9×5.9 region that we call a “footprint.” In order to sample this footprint at the Nyquist rate, a 16-step raster pattern is used that produces 256 spectra per footprint. The main body of the cloud was covered by 80 footprints in approximately an 8×10 pattern (α vs. δ). Additionally, two 4×2 extensions were mapped in the southeast and southwest corners of the map consisting of 96 footprints with a total of 24,576 spectra.

The spectra were obtained in frequency-switching mode with a frequency throw of ± 2 MHz. The data were sampled with a 1024-channel autocorrelator configured to give a resolution of nearly 20 kHz per channel, equivalent to a velocity resolution of 0.051 km s^{-1} . Frequency switching over 4 MHz ensured that both the signal and reference spectra were in the bandpass, and after folding together the signal and reference bandpasses, the velocity coverage ranged from -11 to 16 km s^{-1} with respect to the LSR and was centered at the nominal cloud velocity of 3 km s^{-1} . Integration times were adjusted to give typical rms noise values for the ^{12}CO data of about 0.7 K in units of antenna temperature, T_A^* . To convert T_A^* into T_{mb} , the main-beam brightness temperature, T_A^* is divided by 0.45, the main-beam efficiency of the 14 m telescope at 115 GHz (M. Heyer 2002, private communication). If one wants to convert T_A^* to T_R , the radiation temperature, the relationship is $T_R = T_A^* / [\eta_{\text{fss}} \eta_c]$, where η_{fss} is the forward-scattering and spillover efficiency, which for the 14 m telescope at 115 GHz is 0.7 (M. Heyer 2002, private communication). The quantity η_c is the source filling factor, which can be assumed to be unity because the angular extent of MBM 40 is nearly $1^\circ \times 1^\circ$.

The ^{13}CO (1–0) data were obtained at the 12 m radio telescope of the National Radio Astronomy Observatory (NRAO)³ during three principal runs in 1998 October, 1999

June, and 2000 May. Some additional data were obtained remotely during intervening times. At 110 GHz, the beamwidth is $58''$, which corresponds to 0.034 pc for MBM 40. The data were obtained in frequency-switched mode using the 30 kHz filter bank, which has a velocity resolution of 0.08 km s^{-1} per channel. The frequency throw was $\pm 2 \text{ km s}^{-1}$ and resulted, after folding, in a velocity coverage of 10 km s^{-1} . Integration times ranged from 2 to 5 minutes, resulting in an rms noise figure of 0.1–0.2 K in units of T_R^* , the antenna temperature corrected for forward scattering and spillover. Assuming that η_c is unity, T_R^* equals T_R . Mapping in ^{13}CO was performed using 10×10 grids—which we call “tiles”—with each pixel separated by $20''$ so that each tile covers a $3/3 \times 3/3$ region. Nineteen tiles were observed in an approximately 3×6 diagonal pattern along the principal molecular ridge of the cloud (see Fig. 1). Two of the tiles were not completely covered so that the total number of ^{13}CO spectra is 1866 along the principal molecular ridge.

In addition to the ^{13}CO (1–0) spectra described above, two of the ^{13}CO tiles and two additional narrow strips were observed at the 12 m telescope in the ^{12}CO (2–1) transition at 230 GHz after the telescope had been transferred from NRAO to the University of Arizona. The sampling was still every $20''$ even though the beam at this frequency is $30''$. The velocity resolution of these observations is 0.13 km s^{-1} , but all other observing parameters are similar to those of the ^{13}CO observations. Both tiles were along the principal molecular ridge of MBM 40. One 2×10 beam strip was observed on the eastern ridge of the cloud (see Fig. 1), and the other was obtained at the confluence of the two ridges in the northern part of the molecular emission.

Neutral hydrogen was mapped in the immediate vicinity of MBM 40 using the Arecibo 305 m radio telescope near Arecibo, Puerto Rico.⁴ At 1420 MHz the beamwidth of the L -narrow dual-polarization receiver is $3/1 \times 3/5$, which corresponds to ~ 0.1 pc at the cloud distance. The sensitivity of the telescope is $8\text{--}10 \text{ K Jy}^{-1}$, and other characteristics of the system are detailed in an Arecibo internal memo (Heiles et al. 2000). The data were taken in a raster pattern in right ascension. Fifteen spectra composed each row (given the sampling, each row was $30'$ in length), and there were 17 rows per grid. For MBM 40, 32 grids covering a $4^\circ \times 2^\circ$ region of the sky ($15^{\text{h}}58^{\text{m}} < \alpha < 16^{\text{h}}14^{\text{m}}$ and $21^\circ 0' < \delta < 23^\circ 0'$ [B1950.0]) were observed. The autocorrelator was divided into four sections each with 2048 channels and 3.125 MHz bandwidth. The two polarizations were observed redundantly and added to produce the final map. The velocity coverage was 660 km s^{-1} centered on 0 km s^{-1} with respect to the LSR, giving a velocity resolution of 0.32 km s^{-1} . The bandpass shape was distinct, stable from grid to grid, and removed from each of the 8160 spectra. Each spectrum was also calibrated, gain-corrected, and converted into a three-dimensional data cube (α , δ , and v_{LSR}) using IDL and Arecibo software written primarily by Phil Perillat and Snežana Stanimirović. The final map was regridded to an effective resolution of $3/9$ and has an rms noise level of $\sim 0.2 \text{ K}$ per channel in T_A . Conversion to T_B can be made by $T_B = T_A / \eta_B$, where $\eta_B \sim 0.5$ (P. Perillat 2002, private communication) during our observing run. After our

² FCRAO is supported in part by the National Science Foundation under grant AST 94-20159 and is operated with permission of the Metropolitan District Commission, Commonwealth of Massachusetts.

³ NRAO is operated by Associated Universities, Inc., under contract with the National Science Foundation.

⁴ The Arecibo Observatory is part of the National Astronomy and Ionosphere Center, which is operated by Cornell University under a cooperative agreement with the National Science Foundation.

FIG. 1.— ^{12}CO (1–0) channel maps based on the FCRAO data set between 2.2 and 3.9 km s^{-1} , as labeled. The x - and y -axes are along right ascension and declination, respectively, and are expressed in parsecs. The (0, 0) position corresponds to an α and δ of $16^{\text{h}}14^{\text{m}}08^{\text{s}}$ and $21^{\circ}20'12''$ (J2000.0), respectively. Nine gray-scale levels divide the interval from 2 to 6 K in steps. Sampling resolution ($45''$ FWHM per beam) is 0.026 pc per beam, with two samples per beam (see text).

observations, the surface of the reflector was readjusted, bringing η_B to 0.75 (Heiles et al. 2000).

3. RESULTS

In Figure 1 we show the ^{12}CO (1–0) channel maps from the FCRAO data set in the velocity range 2.4–3.9 km s^{-1} . The cloud divides into two main ridges of emission forming a hairpin structure, as also found by Lee et al. (2002). The

strongest emission originates in several distinct clumps along the lower, brighter ridge. The highest velocity-integrated ^{12}CO (1–0) main-beam brightness temperatures observed in these regions are about 5–10 K. These regions are clearly visible on the *IRAS* 100 μm image (see Fig. 2). However, as the channel maps show, the large-scale velocity field is highly ordered and dominated by a systematic velocity gradient from the northern to the southern parts of the hairpin, lacking discontinuities in both structure and

FIG. 1.—*Continued*

FIG. 2.—*IRAS* 100 μm image of MBM 40 in units of MJy sr^{-1} . The two ridges forming the hairpin structure are clearly evident. [See the electronic edition of the *Journal* for a color version of this figure.]

FIG. 3.—Integrated ^{13}CO (1–0) emission from the NRAO data set. There are seven shaded levels ranging from the noise level to 2 K km s^{-1} . The x - and y -axes are along right ascension and declination, respectively, and are expressed in parsecs. The (0, 0) position corresponds to α and δ of $16^{\text{h}}09^{\text{m}}12^{\text{s}}$ and $21^{\circ}46'00''$ (B1950.0), respectively. [See the electronic edition of the Journal for a color version of this figure.]

velocity. In this sense, MBM 40 represents as much a “flow” as a molecular cloud. Interestingly, similar hairpin structures with velocity gradients have been found in a number of high-latitude translucent clouds: the Polaris Flare (Falgarone et al. 1998), MBM 12 (Pound, Wilson, & Bania 1990), and our previous study of MBM 16 (LSM99). We discuss the implications of this finding in § 5.

Our ^{13}CO (1–0) observations cover only the region of strongest ^{12}CO emission along the southern ridge. We show the velocity-integrated ^{13}CO emission in Figure 3, and Figure 4 shows the ^{13}CO channel maps. The ^{13}CO closely follows the ^{12}CO emission, even including the gap along the southern ridge between the two brightest clumps. The *IRAS* $100 \mu\text{m}$ image confirms that this gap is not merely an optical depth effect: there are distinct mass concentrations within a more extended diffuse envelope. However, because the lines are about the same velocity width as the centroid difference between the clumps, there is significant overlap between the different components in the channel maps. Our data show that the maximum optical depth, based on peak line intensity ratios obtained in the central channel (3.0 km s^{-1}), is only about 4 based on the variation of the relative integrated emissivities in the two (1–0) transitions (see Fig. 5). The

FIG. 4.— ^{13}CO (1–0) channel maps from the NRAO data set between 2.5 and 3.3 km s^{-1} in steps of $\sim 0.05 \text{ km s}^{-1}$. There are 10 shaded levels from the noise level to 4 K . [See the electronic edition of the Journal for a color version of this figure.]

FIG. 5.—Scatter plot for $\int T_R^* dv$ for both CO isotopes. The optical depth in ^{12}CO is about 4 based on the ratios at the peak emissivity of the ^{13}CO (1–0) and ^{12}CO (1–0) lines at the same velocity interpolated to the same spatial resolution.

line profiles show that only the cores are opaque, consistent with low temperatures and a comparatively low column density.

There is detectable substructure in the integrated ^{13}CO maps down to the limit of our resolution (0.03 pc, considerably smaller than a Jeans length), which is typical of all molecular clouds and is especially true for non-self-gravitating clouds (see, e.g., Falgarone et al. 1998). The CS emission found by Magnani et al. (1996) corresponds to the maxima we find in the ^{12}CO and ^{13}CO and confirms that these regions must have higher density. The CH detections (Magnani et al. 1998) can be used to determine the CO/ H_2 conversion for this cloud [$2 \times 10^{20} \text{ cm}^{-2} (\text{K km s}^{-1})^{-1}$; Magnani & Onello 1995]. We find that the highest ^{12}CO column densities are approximately 10^{21} cm^{-2} . This is lower than the critical column density for Jeans instability of $8 \times 10^{21} \text{ cm}^{-2}$ ($N_J = n\lambda_J$, where λ_J is the Jeans length; MLS93), so the observed density enhancements are not gravitationally bound.

The ^{13}CO emission has a larger transverse intensity variation than the ^{12}CO . Changes in peak emission from 4 K down to the noise level are observed across the ridge boundary within one beam spacing, approximately 0.03 pc (see Fig. 6). Figure 7 displays the co-added profiles that simulate a strip scan across the ridge at the peak of the emission. There is no jump in the centroid velocities across the ridge, nor does the velocity dispersion change with position. Position-velocity diagrams along and transverse to the ridge (Fig. 8) also show the continuity of the velocity across and along the ridge. Thus, rapid changes in intensity show no corresponding velocity changes, suggesting that the rapid falloff in density across the ridge cannot be a simple compression effect.

The molecular hairpin structure is clearly visible in the *IRAS* 100 μm image shown in Figure 2. Even allowing for the differences in angular resolution, the infrared is much more extended than the molecular gas. In particular, on the southwest side of the ridge, the strong 100 μm emission has no associated ^{12}CO (compare also Fig. 11 with Fig. 12; see discussion below). This is clarified by H I observations. The H I channel maps from 5.15 to 1.61 km s^{-1} are shown in

steps of 0.32 km s^{-1} in Figure 9. There are systematic structural changes across the channels, but they are not abrupt. At high positive velocity there is an extended, distinct, ovoid feature that merges at lower positive velocity into background emission. This distinct H I feature was first detected and discussed by Verschuur (1970, 1974) from H I maps at lower resolution (10'). At low positive velocity, we lose the ability to discriminate between the atomic gas associated with MBM 40 and that associated with the rest of the flow. The H I emission associated with the molecular gas extends $\sim 1.6 \text{ km s}^{-1}$ based on the morphology and velocity structure of the two components. This limits the velocity of any detectable shock in the atomic gas to velocity differences greater than a few kilometers per second, but we do not see any discontinuities at this level.

We now compare these three data sets. Figure 10 shows the *IRAS* 100 μm imaging versus H I emission integrated between 0 and 6 km s^{-1} . Figure 11 shows the same *IRAS* image but compared to the H I only in the velocity range of the ^{12}CO emission (2.6–3.5 km s^{-1}). Finally, in Figure 12 we show the integrated ^{12}CO emission superposed on the H I emission from 2.6 to 3.5 km s^{-1} . The strongest H I emission in Figure 12 surrounds the molecular gas. However, the column density of this atomic gas is only $\sim 7 \times 10^{19} \text{ cm}^{-2}$ —too low to form any significant quantity of molecular gas (see, e.g., van Dishoeck & Black 1988). In contrast, the molecular gas in the cloud has column densities in the range $(1\text{--}7) \times 10^{20} \text{ cm}^{-2}$ (Magnani et al. 1996), with the ridge in particular at the upper end of this range. Thus, all the gas that could have become molecular has already done so. Not surprisingly, the *IRAS* emission follows the molecular gas distribution; the region of strongest 100 μm emission corresponds to the component with the highest column density.

4. ANALYSIS

4.1. Line Profiles

To avoid biasing our velocity study with formal assumptions about the intrinsic line profile, we derived all statistical line properties at each location in the cloud by weighting each channel with the corresponding measured intensity. The mean ^{12}CO (1–0) line width over the entire cloud is 0.6 km s^{-1} . However, within the ridge, the ^{12}CO line widths (FWHM) are typically 0.8–0.9 km s^{-1} , while the ^{13}CO line widths (FWHM) are 0.4–0.6 km s^{-1} . This is not surprising because the ^{13}CO is optically thin and samples a more spatially confined region of the ridge. As an example, Figure 13 shows the summed ^{13}CO and ^{12}CO spectra obtained with the NRAO 12 m telescope for the densest tile of the map.

To determine the fluctuations in the centroid velocity, Δv , we removed the systematic motions of the centroid velocity map using both median filtering (15 and 25 points) and boxcar smoothing (25 points). Then at each point the velocity difference was computed by subtracting the smoothed map. The fluctuation surface plot is shown in Figure 14. We find neither residual structure nor velocity correlation length above one beamwidth. In contrast, we found a structured velocity field in MBM 16 that showed a correlation on a scale of a few tenths of a parsec. We described these distinct regions in MBM 16 as analogs of laboratory coherent structures (see LSM99; Hussain 1986). However, we find the same statistical behavior for the line profiles for the entire MBM 40 emission region that we found for an individual

Fig. 6.—Gallery of ^{13}CO (1–0) spectra from the northern portion of the ridge [centered at approximately (1.2 pc, 1.6 pc) from Fig. 3]. All spectra cover 6–0 km s $^{-1}$ and are scaled from -1 to 4 K km s $^{-1}$.

FIG. 7.—Summed ^{13}CO spectra from three different regions along a line of right ascension from the most intense portion of the ridge, adjacent to and just off the ridge. This shows that the velocity dispersion in ^{13}CO does not change as a function of density.

coherent structure in MBM 16 (MLS93). The line profiles are systematically underdispersed (i.e., $\sigma_c < \sigma_i$; Kleiner & Dickman 1985). Specifically, we find for the ^{13}CO data that $\sigma_c = 0.3 \text{ km s}^{-1}$ and $\sigma_i = 0.4 \text{ km s}^{-1}$, suggesting that MBM 40 is a *single* coherent structure. This is actually consistent with our previous results because MBM 16 is much more massive and much more extended than MBM 40. Notably, the whole of MBM 40 fits inside a single coherent structure found in MBM 16 (LSM99).

4.2. Probability Density Function Analyses

The velocity probability density function (pdf) is a useful descriptor of laboratory turbulent flows (see, e.g., Minier & Peirano 2001). Independent point processes, e.g., those usually used to represent fully developed, homogeneous, isotropic, incompressible turbulence, show a Gaussian spectrum of deviations from any mean flow. It has long been known, however, that turbulence follows a multifractal

spectrum in wavenumber because of the fluctuations that dominate the energy dissipation at the smallest scales. This is what is meant by intermittency: large velocity and/or density fluctuations occur with greater probability than for a Gaussian process. This is most easily seen by using a pdf type of analysis.

Two types of pdf analyses are commonly used. If $\Delta v(x, y) = v(x, y) - v_M(x, y)$ is the fluctuation in the velocity at any point (x, y) on a map and the quantity $v_M(x, y)$ is the mean (filtered) velocity obtained from some smoothing technique, then Δv is the quantity usually employed for one-dimensional laboratory pdf analyses, called the *velocity centroid pdf* by Miesch, Scalo, & Bally (1999, hereafter MSB99). This quantity is plotted for MBM 40 in Figure 15. Another method to quantify the flow compares the fluctuations at different points in the map separated by fixed distances. MSB99 call this function the *velocity difference pdf*. This function is the distribution of $\Delta v(x, y) - \Delta v(x + L_x, y + L_y)$, where (L_x, L_y) are prechosen lags. We show our results for the velocity difference pdf in Figure 16 for two separations, 5 and 15 lags. It is clear there is no meaningful difference between these two lags.

The most extensive study of molecular cloud pdfs, MSB99, concentrated exclusively on actively star-forming regions, such as Orion. They found that all pdfs show extended, low-intensity, non-Gaussian wings and are also asymmetric with large kurtosis and dispersion. Once again, we find MBM 40 both mimicking and differing from the star-forming clouds. It is similar in showing strongly non-Gaussian wings. Yet the pdf is strikingly symmetric (see Fig. 15). The differences in these two environments may be important for understanding the pdf results. Star-forming clouds are being stirred internally by winds, jets, bubbles, blisters, etc., that are produced by the embedded stars. These can produce asymmetries in pdfs just by small-number statistics. A few of these energy sources along a line of sight can easily produce big shifts in the symmetry. Any anisotropic velocity field can also introduce an orientation dependence in the pdf. Specifically, it is well known in wind tunnel studies (Pumir 1996; van de Water & Herweijer 1999) that boundary layer (vortical) turbulence shows asymmetric pdfs for streamwise flows, while the same flow transverse is nearly symmetric for all displacements along the flow. In fact, this is a general feature of shear flows. It may be that we are seeing these skewed pdfs in some clouds and not others (such as MBM 40) simply because of geometry. The ubiquity of extended, non-Gaussian pdf wings seems to imply that the same spectrum of broadly distributed turbulent motions applies to both classes of clouds even though the source for the flow, preserved at the largest scales, may differ.

In the laboratory, where Doppler data are not generally available, the pdf is the best way to characterize the three-dimensional fluctuations measured at fixed stations along the flow (Minier & Peirano 2001). Astrophysically, we have the advantage that the gas radiates and provides a direct measurement of the line-of-sight motions so, in effect, each line profile provides the same information as the pdf (see Falgarone & Phillips 1990; Ossenkopf & Mac Low 2002). The derived pdf displays wings that depart from a Gaussian at about the 10% level. Both in the case of a single spectrum and for line profiles formed from single tiles by summing 100 spectra, the same behavior persists; we do not see any significant change in the wings of the profile with scale.

FIG. 8.—Position-velocity diagram for the ^{13}CO (1–0) data. These figures are produced by rotating the ^{13}CO data cube ($\alpha, \delta, v_{\text{LSR}}$) so that the position axes lie along the principal ridges of emission.

FIG. 9a

FIG. 9.—(a) H I channel maps from the Arecibo 305 m telescope. Each channel is 0.32 km s^{-1} wide; channel maps are centered at 5.80, 5.15, 4.51, 3.86, 3.22, and 2.58 km s^{-1} . (b) Same as (a), but with velocities from left to right and top to bottom of 1.93, 1.29, 0.64, 0.00, -0.64 , and -1.29 km s^{-1} . The CO emission covers the range $2.6\text{--}3.5 \text{ km s}^{-1}$. [See the electronic edition of the *Journal* for a color version of this figure.]

Consequently, any dissipation scale must be smaller than the resolution of our ^{13}CO spectra, but we see indications of its presence in the asymmetric profiles obtained from the denser gas. Were we actually resolving the dissipation scale, we would expect intrinsically narrow line profiles with the centroids shifting in velocity by sometimes very large amounts. This is *intermittency*, the more-frequent-than-expected excursion of a velocity and/or density fluctuation compared to Gaussian statistics (McComb 1990; Frisch 1995). The stability of the line profiles, essentially independent of scale, and the similarity of a single line profile to the fluctuation pdf both support the contention that we are sampling within the inertial regime of the cascade, above the dissipation scale and below the source scale.

5. DISCUSSION

A number of translucent clouds at high Galactic latitude have been studied in great detail. These include portions of the Polaris Flare (Falgarone et al. 1998), the Ursa Major clouds (de Vries, Heithausen, & Thaddeus 1987; Pound & Goodman 1997), MBM 12 (Pound et al. 1990), MBM 7 (Minh et al. 1996), and MBM 16 (MLS93; LSM99). Many of the high-latitude molecular clouds, including the Ursa Major clouds and MBM 12, are part of large H I shells or fragments of shells in the local interstellar medium (Gir, Blitz, & Magnani 1994; Bhatt 2000). As such, shocks may play the dominant role in their morphology and dynamics. For instance, Sakamoto (2002) reports ^{12}CO (1–0) observations of three translucent clouds, MBM 32 (part of the Ursa

FIG. 9b

Major high-latitude cloud complex), MBM 54, and MBM 55, obtained using the Nobeyama 45 m telescope with a velocity resolution similar to ours but higher spatial resolution.⁵ For MBM 54, he finds large velocity shifts across the cloud, of the order of 2 km s^{-1} , corresponding to a velocity gradient as large as $40 \text{ km s}^{-1} \text{ pc}^{-1}$. This latter result contrasts with ours since it represents a large change in centroid velocity in a very small region compared to our systematic gradient across the entirety of MBM 40. Sakamoto interprets this and similar very localized velocity shifts detected in MBM 55 as evidence for shock compression at the cloud boundary. It is interesting that the compressed gas in these clouds has not generated any gravitationally bound clumps (see Elmegreen 1993).

⁵ Instead of complete mapping, he used strip scans in right ascension—not necessarily oriented in any symmetric way relative to any of the clouds—and displays the results as position-velocity diagrams.

MBM 40 does not appear to be part of any large swept-up shell of this sort based on the large angular scale ($15^\circ \times 15^\circ$) *IRAS* $100 \mu\text{m}$ maps. This is consistent with our finding that the velocity dispersion does not change as a function of gas density. Whether or not translucent clouds are part of swept-up interstellar shells, several of them, including the subregions of the Polaris Flare, the Ursa Major clouds, and MBM 12, have pronounced hairpin molecular structures similar to MBM 40. The best example is the subregion of molecular gas associated with the Polaris Flare that also shows a systematic velocity field (Falgarone et al. 1998). It is remarkable how similar this region is to MBM 40 (see their Figs 5b and 5c). Although the range of velocities is about twice that seen in MBM 40, the line widths are similar and the cloud also shows nearly continuous velocity variation within a filamentary envelope. A detailed analysis of the velocity field of this region by Ossenkopf & Mac Low (2002) concluded that its turbulence

FIG. 10.—*IRAS* 100 μm contours superposed the H I map from Arecibo. The *IRAS* data range from 1.8 to 10.7 MJy sr^{-1} . The H I data are integrated from -6.0 to 6.0 km s^{-1} and are in units of T_A . To convert the counts in the color bar to units of K km s^{-1} , a multiplicative factor of 0.32 must be used. Conversion to $N(\text{H I})$ in units of cm^{-2} is accomplished by multiplying by 1.8×10^{18} . [See the electronic edition of the *Journal* for a color version of this figure.]

is being driven on scales that must exceed the size of the cloud. This result is consistent with our picture of MBM 40.

To clarify the flow kinematics for MBM 40, we can contrast the atomic and molecular velocity fields. In H I, the eastern side of the cloud is at the largest positive velocity, while the western and southern portions show the least positive values. In contrast, for CO the northern and eastern molecular gas shows the smallest positive velocities. The *differential* radial velocity of the molecular gas with respect to the atomic gas on the eastern side is about -2 km s^{-1} , while on the west and southwest the differential is about 1.5 km s^{-1} . The southern side of the atomic gas blends into gas that is at an LSR velocity near zero. The molecular gas is completely enveloped by a continuous flow. Although the gas properties change abruptly, the dynamics does not. Thus, we conclude that the hairpin structure in MBM 40 is a result

FIG. 11.—Same as Fig. 10, except the H I data are integrated over velocities that encompass the CO emission (2.6 – 3.5 km s^{-1}). [See the electronic edition of the *Journal* for a color version of this figure.]

FIG. 12.—Integrated CO contours superposed on the H I data integrated over the CO velocity (2.6 – 3.5 km s^{-1}). Counts are in units of T_A ; to convert to integrated T_A or $N(\text{H I})$, follow the prescription in the Fig. 10 legend. [See the electronic edition of the *Journal* for a color version of this figure.]

of large-scale shear flows—acting together with and promoting thermal instabilities—rather than shock compression. The critical parameter for growth of a thermal instability is $\eta \equiv t_c/t_d$, the ratio of the cooling to dynamical timescales (Hunter & Whittaker 1989; Sánchez-Salcedo, Vázquez-Semadeni, & Gazol 2002). For a number density $n_{\text{H}} = 10^2$ cm^{-3} and a temperature of 10^3 K, the cooling time is of the order of a few times 10^4 yr. This sets a lower limit of about 10^{-2} pc for the smallest scale structure that can grow in the presence of turbulence with a dispersion of about 0.4 km s^{-1} that we see in MBM 40. This is not much less than the smallest size structures we see in the molecular gas at the

FIG. 13.— ^{12}CO line profile (solid line) and ^{13}CO line profile (dotted line) formed by summing 100 scans in one of the tiles from the NRAO 12 m data set. The tile location is at $16^{\text{h}}08^{\text{m}}50^{\text{s}}.1$, $+21^{\circ}50'50''$ (B1950.0).

FIG. 14.—*Left*: Gray scale of the cloud centroid velocities from the FCRAO data set. The shading runs from 2.6 to 3.5 km s⁻¹, with the lower velocity in black. *Right*: Gray scale of the velocity fluctuations (centroid minus median smoothed surface). The shading runs from -1.0 to 1.0 km s⁻¹, with the lower velocity in black. The plot shows no residual structure in the velocity once the systematic velocity is removed.

limits of our resolution. The hairpin structure could therefore be produced by parsec-scale flows ordering the locally cooling gas.

Turbulence produced by shearing, rather than compressive, flows may account for why the higher density regions in MBM 40 and perhaps other translucent clouds are stable (see, e.g., Reach et al. 1995; Grossman & Heithausen 1992; Heithausen, Bertoldi, & Bensch 2002). This is an important difference between star-forming and non-star-forming clouds. In star-forming clouds the turbulence is driven by internal sources, such as stellar winds and jets, H II regions, and supernova explosions that act over a wide range of scales. Recent numerical simulations show that internally driven turbulence generates—through shock compressions—a complicated network of filamentary and clumpy density fluctuations (see, e.g., Ballesteros-Paredes, Vázquez-Semadeni, & Scalo, 1999; Padoan & Nordlund 1999; Klessen, Heitsch, & Mac Low 2000; Ostriker, Stone, & Gammie 2001; Heitsch, Mac Low, & Klessen 2001) that strongly resemble actual star-forming molecular clouds. Such simulations are, however, usually initiated by injecting energy on a size scale smaller than the computational box and may therefore only apply those that have already formed stars. Most translucent clouds have no internal energetic or dynamical sources; thus, to simulate these requires that the flows be driven externally. The behavior of such systems has yet to be explored numerically in an astrophysical context.

FIG. 15.—¹²CO pdf formed using the difference Δv between the velocity centroid and a 15-point median smoothed surface, the two-dimensional map of which is shown Fig. 14. The dashed line is a Gaussian fit to the peak of the distribution.

FIG. 16.—Velocity difference pdf as a function of lag. The dotted line shows the pdf for five lags, and the dashed line shows the pdf for 15 lags. The similarity of the two plots suggests that there is no correlated velocity structure such as vortex sheets.

6. SUMMARY AND CONCLUSIONS

We have used several data sets to develop a consistent picture of the dynamics of MBM 40. The *IRAS* 100 μ m image shows the global environment of MBM 40. The cloud is not part of a larger swept-up shell of material, although this is common for other high-latitude translucent clouds. The FCRAO 14 m telescope ¹²CO data provide a detailed map of the molecular structure of the cloud: a hairpin structure with two ridges of emission. The ¹²CO data also show that there is a systematic velocity gradient across each ridge of the cloud. The NRAO 12 m telescope ¹³CO data show that the ridges of molecular emission have very sharp density gradients. Significant intensity changes over one-beam spacings (0.03 pc) are observed. However, the line widths are constant over the cloud, suggesting that the density gradients are not the result of shock compression. The Arecibo H I data indicate that the molecular cloud is enveloped by atomic gas with a distinct ovoid shape. This feature is also distinct in *velocity* space, exhibiting a range of few kilometers per second on either side of the radial velocity, corresponding to the peak molecular emission.

Together, these data suggest that the molecular gas is subject to an external shear flow. MBM 40 is an example of an H I structure with a systematic flow that has developed a thermal instability leading to the cooling of a small region into a narrower filament—with neither self-gravity nor shock compression responsible for the condensation. Such an instability is purely local but can be organized by a large-scale flow. Because there is no evidence for externally driven compression, and since the cooling-induced growth of dense regions is ultimately throttled by the dynamical support from externally generated turbulence, it is unlikely for such a cloud to form stars. These conclusions can be tested theoretically using nonspectral codes that allow for shearing and cooling (and self-gravity).

We are not proposing a unique mechanism for molecular cloud turbulence. Rather, we expect that shear flows will act in concert with many other processes, depending on the site and the environment (see, e.g., Hennebelle & Péroult 1999). However, shear flow instabilities can by themselves create

density enhancements that are the seed structures that could—under additional compression—lead to collapse and subsequent star formation. Thus, they may be important in the early epochs of galaxy evolution before the interstellar medium is irreversibly altered by the strongly compressive shocks associated with stellar birth and death.

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