Small Scale Structure of Low Density Gas in a Dark Cloud Envelope: Kinematic Evidence for Phase Transition?

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ABSTRACT

Extensive and sensitive strip-scan observations of the southeastern envelope of Heiles Cloud 2 in Taurus were carried out in $^{12}$CO $J = 1 - 0$ emission with an angular resolution of 15", or 0.010 pc at 140 pc. We discovered in the cloud envelope a number of small scale structures with large linewidths, while in the main body of the cloud relatively narrow linewidth and small velocity gradient was observed. The typical size and linewidth of the small scale features in the cloud envelope is 0.1 pc and 2 km s$^{-1}$, respectively. This linewidth is among the largest of this size observed in non–star-forming regions and even larger than high-mass cores of comparable size. Most of them have low gas density ($\lesssim 10^2$ cm$^{-3}$) and sizes significantly smaller than their corresponding Jeans lengths, and seem stable under external pressure at a level of $10^{3-4}$ K cm$^{-3}$. These features may be evidence for structure formation through thermal instability.

In the cloud envelope, there exist small features with large peak-to-peak separation of velocity centroid ($\sim 7$ km s$^{-1}$) but they suddenly disappear in regions with $A_V \gtrsim 1$. This sudden change of velocity structure may be due to the gas phase transition from two-phase (WNM+CNM) to single CNM phase.

1. Introduction

Envelopes of molecular clouds are primary sites of molecule formation and dissociation. They are often diffuse in gas density and, because of slow dynamical and chemical evolution in low-density regions, they may have preserved initial structure and composition of molecular clouds. Without onset of embedded star formation, they may also have preserved their initial velocity structure. In addition, overlapping of substructures is expected less severe in cloud envelopes than in cloud interiors. Cloud envelopes thus provide keys to understand molecular clouds’ formation/destruction processes and early spatial/velocity structure.

Cloud envelopes have attracted attention of researchers because they provide unobscured view of the complex cloud structure (see, e.g., Falgarone et al. 1998). Early works (Falgarone, Phillips, & Walker 1991; Falgarone, & Phillips 1996) focused primarily on spatial structure and line intensity ratios, and concluded that the molecular component in cloud envelopes has the same structure as the bulk of non–star-forming material (i.e., dense gas) but with very low volume filling factor.

Alternative approach that emphasizes velocity structures and their relation to cloud formation/destruction processes has been made by ourselves through very long strip-scan observations. In our Paper I (Sakamoto et al. 1997) we made high-resolution observations in $^{12}$CO $J = 1 - 0$ emission of a typical giant molecular cloud, L1641 in Orion, including its envelope, and found small-scale structures in the envelope and identified a number of compact regions with broad linewidth. The second targets were high-latitude clouds, where we found a number of sub–Jeans-scale structures and localized velocity shifts (Sakamoto 2002, hereafter Paper II). This is our third paper and we point our target to a typical dark cloud, Heiles Cloud 2 (hereafter HCL2, Heiles 1968) in Taurus.

HCL2 was selected because it is nearby (140 pc, Elias 1978) and is believed free from influences of nearby OB stars and supernova remnants. In this cloud there are a number of evidences for northwest–southeast age gradient. Such evidences include enhanced CI/CO ratio in the southeastern part (Maemawa et al. 1999; Maezawa 2000) and concentration of young stellar objects in the northwestern part of the cloud (see, e.g., Stelzer & Neuhäuser 2001). Also claimed is systematic variation of molecular abundance along the TMC-1 ridge: the southeastern part of the cloud is abundant in carbon-chain molecules such as CCS and cyanopolyynes (both considered to be abundant in the early stage of chemical evolution), while the northwestern part is abundant in molecules considered to be enhanced in the later stage, such as NH$_3$, N$_2$H$^+$, and SO (Hirahara et al. 1992, 1995; Pratap et al. 1997). We therefore focused on the southeastern part of the cloud where Maezawa et al. (1999) found a CI rich gas and concluded it may be in the early evolutionary stage of dense core formation. Here we report an identification of small features with broad linewidths in the envelope of
the cloud through high angular resolution observations.

2. Observations

Strip-scan $^{12}$CO $J = 1 - 0$ observations of the southeastern envelope of HCL2 were made from 2001 March 19 to 23 with the Nobeyama 45 m radio telescope. At 115 GHz, the telescope had a half-power beamwidth of 15$''$ (0.010 pc at the distance of 140 pc). We used central 3 $\times$ 3 beam of the 5 $\times$ 5-beam focal plane array receiver (Sunada et al. 2000), and we consequently took three northwest–southeast parallel strips spaced by 41$''$1. Each strip consisted of 755 spectra spaced by 13$'$7 and stretched about 2$^\circ$.87 (7.0 pc at 140 pc) toward the northwest–southeast direction (Figure 1). Reference centers of the strips were set at $(\alpha_{1950}, \delta_{1950}) = (04^h39^m00^s, +25^\circ15'00'')$, $(04^h39^m02^s, +25^\circ15'29'')$, and $(04^h38^m58^s, +25^\circ14'31'')$, for the central, northeastern, and southwestern strips, respectively, and correspond to the CI peak reported by Maezawa et al. (1999). Pointing of the antenna was calibrated every 1.5 hours using the SiO masers in NML Tau, and its typical error was half of the beam width during the observations. All points except for those at the ends of the strips were observed with all three elements of the array receiver, so that instrumental artifacts are minimized. A digital auto-correlator with a 37.8 kHz resolution (0.1 km s$^{-1}$ at 115 GHz) and a 32 MHz coverage (Sorai et al. 2000) was used in frequency switching mode with throw and modulation rates at 7.685 MHz and 0.25 Hz, respectively. The baselines were very stable and linear baselines were subtracted from the folded spectra. The intensity scale for each beam of the array receiver was calibrated against a black body at ambient temperature, and was then scaled for the sideband rejection ratio correction. We typically integrated for 300 seconds per position in frequency switching mode and got a typical sensitivity of $\sim 300$ mK (km s$^{-1}$)$^{-1/2}$ after folding the spectra and the correction mentioned above. All line intensities given in this paper are antenna temperatures, $T_\text{A}^*$, of Kutner & Ulich (1981), corrected for atmospheric loss, antenna ohmic loss, rearward spillover and scattering, and are to be corrected for the coupling efficiency of the antenna, which was $\approx 0.45$ at the observing frequency for compact sources and was larger than this value (up to $\approx 0.7$) for extended objects in our strip.

Follow up mapping observations of a selected area was carried out during 2002 December 17 to 19. During this run, 24 out of the 5 $\times$ 5-beam focal plane array receiver were available. The grid was set to match with the strips, with the X axis in accordance with the central strip and the Y axis to the northeast. Coarse distribution of molecular gas in a 15$^\prime$8 $\times$ 16$^\prime$4 (0.64 $\times$ 0.67 pc) area was first measured with a sampling of 41$''$1. Selected 13$''$2 $\times$ 6$''$6 part of the area was then mapped with a 13$''$7 sampling.
3. Results

3.1. Spatial and Velocity Structure

Our northwest-southeast strip-scan observations with the $3 \times 3$-beam focal plane array receiver generated three parallel position-velocity diagrams spaced by $41''/1$ (0.028 pc at 140 pc) as shown in Figure 2. The position-velocity diagrams kinematically resolve complex velocity features in this region. Global appearance of these diagrams mimics each other, confirming that relative calibration of the element receivers are accurate enough.

Appearance of the position-velocity diagrams dramatically changes near the middle of the strips. In the northwestern half (i.e., the upper half) of these diagrams, the position-velocity diagrams are typical ones observed in dark clouds: (1) lines are narrow, (2) velocity gradient of individual features is small, (3) peak antenna temperature is nearly constant at around 6 K. It is also shown in the positional profiles of integrated intensity and peak intensity in Figure 3. All three strips provide almost identical appearance in the northwestern half. It is interesting that the velocity structure of molecular gas near the CI peak of Maezawa et al. (1999) shows no outstanding difference with that in cloud interior regions.

By contrast, the velocity structure in the southeastern part is very peculiar as illustrated in Figure 4, which shows close-up of the southeastern half of the position-velocity diagrams. There are a number of small-scale structures with large linewidth with their projected half-maximum lengths\(^1\) along the strips of $\sim 0.1$ pc. They can be found, for instance, near positional offset $X = +530$, $v_{\text{LSR}} = +4.5 \text{ km s}^{-1}$, near $X = +400$, $v_{\text{LSR}} = +5.0 \text{ km s}^{-1}$, and near $X = +435$, $v_{\text{LSR}} = +4.0 \text{ km s}^{-1}$ in Figure 4. The smallest structures have sizes comparable to the beam size (0.010 pc), and include the one found near $X = +322$, $v_{\text{LSR}} = +2.0 \text{ km s}^{-1}$ in the central strip of Figure 4. Some of these velocity features have sharp boundaries that clearly define themselves, with faint emission sometimes interconnecting them to form a group of velocity components with steep velocity gradient. We also found compact but faint ($\sim 1$ K) structures near $X = +560$, $v_{\text{LSR}} = +8.5 \text{ km s}^{-1}$ and near $X = +350$, $v_{\text{LSR}} = +2.5 \text{ km s}^{-1}$. Since they are isolated from intense CO features both in space and in velocity, they are quite unlikely artifacts due to far sidelobe of the antenna, but are diffuse components that contain CO gas. Although found in CO emission, some of these features in the southeastern part may be mostly atomic, due to the difference in dissociation energy of CO (11.1 eV) and H\(_2\) (4.8 eV) molecules. Considering that the Jeans length $c_s/(G\rho)^{-1/2}$ corresponds to $0.6(T_k/10 \text{ K})^{1/2}(n(\text{H}_2)/10^3 \text{ cm}^{-3})^{-1/2}$ pc, most of these

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\(^1\)Although we did not map these clumps, the sizes estimated from the half-maximum projected lengths along the strips may not differ much from their actual sizes unless their major axis align with the strip.
structures are unlikely to be formed by gravitational contraction.

Velocity channel maps of the features near $X = +400$ (Figure 5) clearly illustrates that the features are very compact in size ($R \lesssim 0.1\,\text{pc}$), are sometimes very filamentary with large projected aspect ratio ($\gtrsim 3$), are isolated from the main body of the molecular cloud, and have very complex internal velocity structure. It is noteworthy that compact filamentary structures are commonly observed in low density molecular gas where self gravity is completely negligible.

Appearance of these features in the position-velocity diagrams resembles those discovered in high-latitude clouds in Paper II, except that individual features are less overlapped in the present case. For some of the features the large linewidth is in part due to large velocity gradient ($>10\,\text{km}\,\text{s}^{-1}\,\text{pc}^{-1}$). Peak-to-peak velocity separation of the velocity centroids of individual features due to relative motion of individual features is assessed with averaged profile in Figure 6. In the southwestern part, large velocity separation is obvious and is $\sim 7\,\text{km}\,\text{s}^{-1}$.

If these are characteristic in cloud envelopes, similar features may be found also along the line of sight toward cloud interior regions where envelopes are projected in foreground and background. Actually features similar to these are also visible in the northwestern half, for instance, near $X = +70$, $v_{\text{LSR}} = +4\,\text{km}\,\text{s}^{-1}$ in Figure 2, where compact peculiar-velocity component is distinguishable in the blue-shifted side of the main component. Because similar structures were reported in a giant molecular cloud (Paper I) and in high-latitude clouds (Paper II), this kind of velocity features appear common in dark clouds.

### 3.2. Gas Density, Column Density and Visual Extinction

As shown in Figure 3, peak brightness temperature of these smallest clumps is 6 K or less after a factor $\sim 2$ correction for the beam efficiency for compact sources. The observed low CO brightness implies low excitation temperature or low opacity or low beam filling factor or their combinations. Provided that the beam filling factor of the emitting region is very close to unity and that gas kinetic temperature in this translucent environment is higher than 15 K, the CO $J = 1 - 0$ brightness temperature seems significantly lower than the kinetic temperature\(^2\). In such cases the peak intensity of CO $J = 1 - 0$ emission is only

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\(^2\)Kinetic temperature of molecular hydrogen in $1 < A_V < 5$ regions determined by the recent FUSE survey is $68 \pm 15\,\text{K}$ (Rachford et al. 2002). Theoretical models also predict kinetic temperature larger than 30 K for $A_V < 3$ (see, e.g., Hollenbach, Takahashi, & Tielens 1991).
very weakly dependent on kinetic temperature and we can set upper limit to the gas density (see, Appendix A of Paper II), and the deduced gas density of these clumps is lower than \( \sim 10^2 \text{ cm}^{-3} \) (see, Figure 9 of Paper II).

Alternative explanation is that the beam filling factor is substantially smaller than unity and the gas density is much higher than the above value (see, e.g., Falgarone & Phillips 1996), but there are difficulties in explaining the stability of these features as will be discussed in the next subsection. In addition, the assumption of very small beam filling factor and high excitation temperature in weak CO emitting regions has difficulties in explaining deep absorption features caused by diffuse clouds often observed even with fairly large beams. The low CO \( J = 2 - 1/J = 1 - 0 \) ratio measured with large beam (\( \sim 0.4 \), Hayashi et al. unpublished) supports low excitation temperature rather than low beam filling factor with very high excitation temperature in this region.

Column density of molecular gas were estimated by adopting the \( N(\text{H}_2)/I(\text{CO}) \) conversion factor for low-density regions (\( 2 \times 10^{20} \text{ cm}^{-2} (\text{K km s}^{-1})^{-1} \); Sakamoto 1999). This conversion factor is consistent with those measured in high-latitude clouds ((0.3–6.8)\( \times 10^{20} \) with an average value of \( 1.9 \times 10^{20} \) and a median value of \( 1.2 \times 10^{20} \text{ cm}^{-2} (\text{K km s}^{-1})^{-1} \); Magnani & Onello 1995) and has theoretical background, and thus was considered appropriate. After correcting the integrated intensity presented in Figure 3 by a factor \( \sim 2 \) for compact sources in cloud envelope and a factor \( \sim 1.3 \) for extended sources and by assuming that all the gas is molecular, the molecular column density is deduced to be \( \sim 4 \times 10^{21} \text{ cm}^{-2} \) near the northwestern end of the strip and it gradually reduces down to \( \sim 1 \times 10^{21} \text{ cm}^{-2} \) near the southeastern end. The column density\(^3\) of the interface region where velocity structure drastically changes corresponds to \( \sim 2 \times 10^{21} \text{ cm}^{-2} \). This column density of molecular gas seems agree with that expected from the visual extinction and the \((N(\text{H}_2) + \frac{1}{2}N(\text{H}_1))/A_V\) ratio (0.94 \( \times 10^{21} \text{ cm}^{-2} \text{ mag}^{-1} \); Bohlin, Savage, & Drake 1978; Sneden et al. 1978). The visual extinction map produced by Dobashi et al. (2002) on the basis of Digitized Sky Survey I using the star count technique (Figure 1), which seems consistent with the previous visual extinction measurements by Cernicharo & Guélin (1987) in the overlapped regions, shows that \( A_V \sim 4 \) near the northwestern end of the strip and gradually reduces down to \( A_V \sim 0.5 \) near the southeastern end, corresponding to \( \sim 4 \times 10^{21} \) and \( \sim 5 \times 10^{20} \text{ cm}^{-2} \), respectively.

\(^3\)Note, however, the column density we observed is the value along the interface and is not the value accumulated along the line perpendicular to the interface, and may overestimate the true value of interest. In addition, we assumed that all the gas is molecular. Care must be taken when we compare this result with theoretical results.
3.3. Size-Linewidth Relation and Dynamical State

Internal motion of individual clumps found in HCL2 envelope is dominated by non-thermal motions, as is illustrated in Figure 7 that plots non-thermal linewidths ($\Delta v_{NT} \equiv [(\Delta v)^2 - 8 \ln 2 (kT/m)]^{1/2}$) of individual clumps as a function of their sizes. Kinetic temperature was assumed 15K to calculate the thermal width in this region and the result is not very sensitive to this assumption.

Non-thermal linewidths of the clumps in these clouds are significantly larger than those expected from the size-linewidth relation for low-mass cores presented by Fuller & Myers (1992), comparable to or even larger than those for high-mass cores presented by Caselli & Myers (1995), and comparable to those for clumps in high-latitude clouds presented in Paper II. Given very small size, small gas density and large linewidth, these features are unlikely to be bound by their self gravity. Without other supports, they will dissipate in a time scale comparable to sound crossing time ($10^{4-5}$ yr).

A probable explanation of the abundance of these features with large linewidths is that they are confined by external pressure. Neglecting effects of magnetic field, the virial equilibrium equation for an isothermal sphere of radius $R$, gas density $n$(H$_2$), and linewidth $\Delta v$ under the external pressure $P_{\text{ext}}/k$ can be rewritten as (Heithausen 1996),

$$
\left( \frac{\Delta v}{\text{km s}^{-1}} \right)^2 = 0.05 \left( \frac{n(\text{H}_2)}{\text{cm}^{-3}} \right)^{-1} \left( \frac{P_{\text{ext}}/k}{\text{K cm}^{-3}} \right) + 5 \times 10^{-4} \left( \frac{R}{\text{pc}} \right)^2 \left( \frac{n(\text{H}_2)}{\text{cm}^{-3}} \right). \tag{1}
$$

In the present case ($\Delta v \sim 1 \text{ km s}^{-1}$, $R \lesssim 0.1 \text{ pc}$, $n(\text{H}_2) \lesssim 10^2 \text{ cm}^{-3}$), the term of the self gravity is negligible and the Equation (1) is approximated by,

$$
\frac{P_{\text{ext}}/k}{\text{K cm}^{-3}} \simeq 20 \left( \frac{\Delta v}{\text{km s}^{-1}} \right)^2 \left( \frac{n(\text{H}_2)}{\text{cm}^{-3}} \right), \tag{2}
$$

and the external pressure of order $10^{3-4} \text{ K cm}^{-3}$, which is typical in the Galactic diffuse interstellar medium (Myers 1978; Keto & Myers 1986), is sufficient to confine these low-density features. Most of these features may be thus almost purely pressure confined.

4. Discussion

4.1. Origin of Sub–Jeans-Length Structures

In our Paper II we tested two possible mechanisms for formation of these sub–Jeans-length structures, i.e., thermal instability and the Kelvin-Helmholtz instability, and con-
cluded that thermal instability is more likely. Similar arguments also apply in the present case.

According to the recent theory by Koyama & Inutsuka (2000; 2002), molecular components smaller than Jeans length can be formed through the thermal instability of atomic gas in shocked layers. Gas density of \( \sim 10^2 \text{ cm}^{-3} \) can be realized from pre-shocked gas with ram pressure larger than \( 10^{3.5} \text{ K cm}^{-3} \) (see, Figure 8 of Koyama & Inutsuka 2000). Since the length scale of the thermal instability is determined by sound-crossing length in cooling time, the size of the cloudlets formed through the thermal instability becomes smaller owing to faster cooling if the initial gas density is large, and the shortest wavelength of unstable perturbation is \( \sim 0.0001 \text{ pc} \) (Koyama & Inutsuka 2000). Sub-Jeans-length structures with sizes up to \( \sim 0.2 \text{ pc} \) are expected to form through coagulation of these small cloudlets with a similar timescale (Koyama & Inutsuka 2001, private communication).

The Kelvin-Helmholtz instability might produce similar small-scale structure through stripping of a fraction of molecular gas from an already molecular gas cloud. In this case, however, it will take \( \sim 10^6 \text{ yr} \) to travel 2 pc with a transverse velocity of 2 km s\(^{-1}\). The observational fact that some of these structures are isolated from the molecular gas reservoir with a projected separation up to 2 pc (see, Figures 1 and 2) makes it unlikely that they were stripped off from the natal molecular gas.

### 4.2. What is Happening in the Transition Zone?

One of the most striking features is the sudden change of velocity structure, from relatively calm cloud interior to very turbulent periphery. This may be explained by the scenario of two-phase interstellar clouds (e.g., Inutsuka & Koyama 1999; Wolfire et al. 1995 and references therein). According to Figure 3 of Inutsuka & Koyama (1999), interstellar clouds under pressure of \( 10^{3.5} \text{ K cm}^{-3} \) will be mostly composed of cold neutral medium (CNM; \( T_k \sim 50 \text{ K} \)) if they have large enough column density (> \( 5 \times 10^{19} \text{ cm}^{-2} \)), and will be composed of the mixture of warm neutral medium (WNM; \( T_k \sim 8 \times 10^3 \text{ K} \)) and CNM at \(< 5 \times 10^{19} \text{ cm}^{-2} \). In regions where two phases coexist, clumpy CNM in WNM may have large velocity dispersion (up to the thermal velocity width of 19 km s\(^{-1}\) for HI gas at \( 8 \times 10^3 \text{ K} \)) and collide with each other, resulting in increase of column density, and the two-phase medium may lose its warm state and is expected to collapse rapidly. In the course of this evolution, drastically change of dynamical state of interstellar matter will be observed. We may have found evidence for this change of dynamical state of interstellar gas due to phase transition, though the absolute location of the transition zone seems higher in \( A_V \) than the theoretical prediction.
5. Summary

We made strip-scan observations of the southeastern envelope of Heiles Cloud 2 in $^{12}$CO $J = 1 - 0$ emission with an angular resolution of 15" (0.010 pc at 140 pc) and sensitivity of $\sim 300\,\text{mK}\,(\text{km\,s}^{-1})^{-1/2}$. In the position-velocity diagrams we discovered velocity features with the following characteristics:

- Their typical size is 0.1 pc, and the smallest ones have sizes comparable to the beam size.

- Their typical linewidth is $2\,\text{km\,s}^{-1}$, which is among the largest of this size observed in non-star-forming regions and even larger than high-mass cores of comparable size.

- Their gas density deduced from their low CO brightness temperature is $\lesssim 10^2\,\text{cm}^{-3}$, provided that the beam filling factor of the emitting region is very close to unity and that gas kinetic temperature in this translucent environment is higher than 15 K.

- These features are significantly smaller than the Jeans lengths.

- In spite of their large linewidth and small size, they seem to be confined by external pressure at a level of $10^{3-4}\,\text{K}\,\text{cm}^{-3}$, which is typical of the Galactic interstellar matter, because of their low gas density. These features may be evidence for structure formation not through self gravity but probably through thermal instability.

- These small features in the cloud envelope have large peak-to-peak separation of velocity centroid ($\sim 7\,\text{km\,s}^{-1}$) that is very supersonic for cold neutral medium (CNM; $T_k \sim 50\,\text{K}$) but subsonic for warm neutral medium (WNM; $T_k \sim 8 \times 10^3\,\text{K}$). They suddenly disappear in regions with $A_V \gtrsim 1$. This sudden change of velocity structure may be due to the gas phase transition from two-phase (WNM+CNM) to single CNM phase.

All these characteristics imply that the envelopes of dark clouds are more like translucent clouds rather than the main body of dark clouds, and thus they are the sites of early stages of molecular cloud evolution. Compact velocity features with large linewidth and velocity gradient are characteristic in molecule-forming regions, and we propose search for these peculiar velocity structures as a good way in pinpointing molecule-forming regions.

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Fig. 1.— (a) Loci of the $^{12}$CO $J = 1 - 0$ strip scan overlaid on IRAS 100 $\mu$m image of the $5^\circ \times 5^\circ$ area of Heiles Cloud 2. Cross marks the reference center position at $(\alpha_{1950}, \delta_{1950}) = (04^h39^m00^s, +25^\circ15'00'')$, which corresponds to the CI peak of Maizawa et al. (1999). North is up and east is left. Coordinates of the northwestern and southeastern ends of the central strip scan are $(\alpha_{1950}, \delta_{1950}) = (04^h37^m11^s, +25^\circ39'32''5)$, and $(04^h46^m04^s, +23^\circ37'48''2)$, respectively. (b) Same as (a) but overlaid on $A_V$ map of the $5^\circ \times 5^\circ$ area produced by Dobashi et al. (2002) on the basis of Digitized Sky Survey I using the star count technique. The angular resolution is 6$'$ and the sampling is every 2$'$ along the Galactic coordinate. The lowest contour is at 0.5 mag with subsequent contours spaced every 1.0 mag starting from 1.0 mag. Noise level is $\sim 0.5$ mag (3$\sigma$). (c) Same as (a) but overlaid on $^{12}$CO $J = 2 - 1$ integrated intensity map of the $5^\circ \times 5^\circ$ area taken with the Very Small Telescope-1 (Hayashi et al. unpublished). The beamsize is 9$'$ $\pm$ 1$'$ and the sampling is every 7.5$'$. 
Fig. 2.— (a) Position-velocity diagram of $^{12}$CO $J = 1 - 0$ emission toward the envelope of Heiles Cloud 2 for the northeastern strip. Position is the offset toward southeast from the CI peak of Maezawa et al. (1999) at $\alpha_{1950} = 04^h39^m02^s$, $\delta_{1950} = +25^\circ15'29''$. The length of the strip is about 2°.87 and it corresponds to 7.0 pc at the adopted distance of 140 pc to the cloud. Intensity is not corrected for the beam efficiency. (b) Same as (a) but for the central strip, which runs parallel to the northeastern strip offset by 41''1 (0.028 pc at 140 pc) to the southwest. Position is the offset from $\alpha_{1950} = 04^h39^m00^s$, $\delta_{1950} = +25^\circ15'00''$. (c) Same as (a) but for the southwestern strip, which runs parallel to the central strip offset by 41''1 to the southwest. Position is the offset from $\alpha_{1950} = 04^h38^m58^s$, $\delta_{1950} = +25^\circ14'31''$. 
Fig. 3.— (a) Positional profile of $^{12}$CO $J = 1–0$ emission toward the southeastern envelope of Heiles Cloud 2 in intensity integrated over 0–10 km s$^{-1}$. Position is the offset toward southeast from the CI peak of Maezawa et al. (1999) at $\alpha_{1950} = 04^h39^m00^s$, $\delta_{1950} = +25^\circ15'00''$. The length of the strip is about 2\degree.87 and it corresponds to 7.0 pc at the adopted distance of 140 pc to the cloud. Intensity is not corrected for the beam efficiency. (b) Same as (a) but in peak intensity corrected for noise in which small scale features are more clearly visible.
Fig. 4.— (a) Position-velocity diagram of $^{12}$CO $J = 1 - 0$ emission toward the envelope of Heiles Cloud 2 for the northeastern strip. Position is the offset toward southeast from the CI peak of Maezawa et al. (1999) at $\alpha_{1950} = 04^h39^m02^s$, $\delta_{1950} = +25^\circ15'29''$. Intensity is not corrected for the beam efficiency. (b) Same as (a) but for the central strip. Position is the offset from $\alpha_{1950} = 04^h39^m00^s$, $\delta_{1950} = +25^\circ15'00''$. (c) Same as (a) but for the southwestern strip. Position is the offset from $\alpha_{1950} = 04^h38^m58^s$, $\delta_{1950} = +25^\circ14'31''$. 
Fig. 5.—$^{12}$CO $J = 1 - 0$ velocity channel maps of a part of molecule-atom transition zone in the LSR velocity channels from 0 to 10 km s$^{-1}$ spaced by 1 km s$^{-1}$. Gray scale is brightness temperature on the $T_R^*$ scale averaged over each 1 km s$^{-1}$ wide channel shown at the top right corner. The X axis extends toward southeast from the CI peak of Maezawa et al. (1999) at $\alpha_{1950} = 04^h39^m02^s$, $\delta_{1950} = +25^\circ15'29''$ and the Y axis is toward northeast. One grid corresponds to 13$''$.7 and is comparable to the telescope’s beamwidth. Note that less than half of the area was sampled every 13$''$.7 and the rest was undersampled by a factor of 9.
Fig. 6.— Averaged line profiles over the three strips in the northwestern ($-60 < X < +270$) and southeastern ($+270 < X < +600$) parts. Note that each profile samples the same volume of the sky.
Fig. 7.— Size-linewidth relations for $^{12}$CO $J = 1 - 0$ clumps in Heiles Cloud 2 (filled squares). The relations for high-mass cores in Orion (open circles) taken from Caselli & Myers (1995), low-mass cores in dark clouds (open squares) from Fuller & Myers (1992), and $^{12}$CO $J = 1 - 0$ clumps in high-latitude clouds (gray circles) from Sakamoto (2002) are plotted for comparison. Lines indicate best fits of the size-linewidth relations for high-mass cores (solid line) and low-mass cores (dashed line).