OBSERVATIONS OF [C II] 158 MICRON LINE AND FAR-INFRARED CONTINUUM EMISSION TOWARD THE HIGH-LATITUDE MOLECULAR CLOUDS IN URSA MAJOR

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ABSTRACT

We report the results of a rocket-borne observation of the [C II] 158 μm line and far-infrared continuum emission at 152.5 μm toward the high-latitude molecular clouds in Ursa Major. We also present the results of a follow-up observation of the millimeter 12CO J = 1 → 0 line over a selected region observed by the rocket-borne experiment. We have discovered three small CO cloudlets from the follow-up 12CO observations. We show that these molecular cloudlets, as well as the MBM clouds (MBM 27, 28, 29, and 30), are not gravitationally bound. Magnetic pressure and turbulent pressure dominate the dynamic balance of the clouds.

After removing the H I-correlated and background contributions, we find that the [C II] emission peak is displaced from the 152.5 μm and CO peaks, while the 152.5 μm continuum emission is spatially correlated with the CO emission. We interpret this behavior by attributing the origin of the [C II] emission to the photodissociation regions around the molecular clouds illuminated by the local UV radiation field. We also find that the ratio of the molecular hydrogen column density to the velocity-integrated CO intensity is 1.19 ± 0.29 × 10^{20} cm^{-2} (K km s^{-1})^{-1} from the FIR continuum and the CO data. The average [C II]/FIR intensity ratio over the MBM clouds is 0.0071, which is close to the all-sky average of 0.0082 reported by FIRAS on the COBE satellite. The average [C II]/CO ratio over the same regions is 420, significantly lower than in molecular clouds in the Galactic plane.

Subject headings: infrared: ISM: lines and bands — ISM: clouds

1. INTRODUCTION

The [C II] (P_{3/2} → P_{1/2}) 157.7 μm line emission is thought to be an important coolant of the diffuse interstellar medium (Dalgarno & McCray 1972; Spitzer 1978). In recent theoretical studies, the [C II] line dominates the cooling of the cold neutral medium (Wolfire et al. 1995) and low-density photodissociation regions (PDRs) around the surface of molecular clouds (Hollenbach, Takahashi, & Tielens 1991). The PDR models (Tielens & Hollenbach 1985; Hollenbach et al. 1991) are in agreement with observations of [C II] emission from individual star-forming regions at the edge of the molecular clouds and diffuse [C II] emission from the Galactic plane (Shibai et al. 1991; Wright et al. 1991). Observation of [C II] emission from PDRs, however, has been limited to regions with G_0 > 10, where G_0 is the far-ultraviolet (FUV) field strength normalized to Habing's (1968) estimate of the local interstellar flux, owing to the low brightness of [C II] emission from PDRs with G_0 as small as that found locally. Observations of local high-latitude molecular clouds thus provide a unique opportunity to study such PDRs. The high-latitude molecular clouds studied in this paper are believed to be located in the solar neighborhood (Magnani, Blitz, & Mundy 1985, hereafter MBM).

Observation of diffuse [C II] line emission at high Galactic latitudes is, however, only possible from space, due to the low brightness of the line from these regions. Balloon-borne and airborne observations do not have great enough sensitivity, owing to the enormous background of the earth's atmosphere and from the ambient-temperature telescope. FIRAS on the COBE satellite has observed the [C II] line over almost the entire sky with a 7° beam (Wright et al. 1991; Bennett et al. 1994); however, this is too large to observe [C II] emission from high-latitude molecular clouds.

In 1992 February we made a rocket-borne observation of the [C II] 158 μm line and far-infrared (FIR) continuum emissions of a region at high Galactic latitude in Ursa Major, attaining higher sensitivity and higher angular resolution (0°/6) than COBE/FIRAS. Details of the experiment are described in Matsuura et al. (1994). The correlation of the [C II] line with H I column density in regions without appreciable CO emission has already been reported by Bock et al. (1993). The FIR continuum observations of both atomic and molecular regions have been presented by Kawada et al. (1994).

The main purpose of this paper is to present the first observation of the [C II] line from high-latitude molecular clouds. We also report the results of a follow-up obser-
viation of the millimeter $^{12}$CO $J = 1 \rightarrow 0$ line with a 4 m millimeter telescope at Nagoya University. The rocket-borne observations pass over high-latitude molecular clouds studied by MBM: MBM 27, 28, 29, and 30. $^{12}$CO emission from these high-latitude clouds (hereafter MBM clouds) has already been well studied by de Vries, Heithaussen, & Thaddeus (1987, hereafter VHT). In previous works (Bock et al. 1993; Kawada et al. 1994) we implicitly assumed that there were no molecular regions except those reported by VHT. The follow-up CO observation enables us to check the validity of this assumption. In this paper, we assume that the distance to the Ursa Major clouds is $D = 100$ pc, as adopted by VHT. Penprase (1993) constrained the distance of the clouds by optical absorption line observations toward bright stars with known distances, 100 pc $< D < 120$ pc.

In the following discussion, we describe the rocket-borne observation and results (§2) and the millimeter CO observation and results (§3); we then discuss the physical properties of the molecular clouds and the origin of the [C II] emission from the MBM clouds (§4).

2. ROCKET-BORNE OBSERVATION AND RESULTS

2.1. Observation

The rocket-borne instrument consists of an absolute twocchannel spectrophotometer at the focus of a 10 cm liquid helium–cooled telescope that measures [C II] $157.7 \mu$m velocity-integrated flux (LC channel) and nearby continuum flux at $152.5 \mu$m (CC channel) simultaneously. Specifications of the spectrophotometer are summarized in Table 1.\(^2\) Details of the instrument and the method of [C II] observations, respectively, can be found in Matsuura et al. (1994) and Bock et al. (1993).

The instrument was integrated with the sounding rocket S-520-15 of the Institute of Space and Astronautical Science (ISAS) in Japan and launched on 1992 February 2 from the Kagoshima Space Center of the ISAS. Observations began at 130 s after launch, when a lid covering the telescope was opened, and ended at 480 s when the instrument was separated from the rocket payload.

Observed regions are shown in Figure 1. For more than half of the observation time, the telescope was pointed at the HI hole at ($l, b$) $\sim (151^\circ, 52^\circ)$. From 220 s to 310 s after launch, the telescope scanned along a triangular path, shown in Figure 1, through the high-latitude molecular clouds (MBM clouds) and over the FIR bright galaxy M82, which was observed for in-flight calibration of the instrument.

2.2. Results

The data used in this paper are the LC and CC data obtained between 222 and 357 s after launch, during which time the triangular scanning observation and a part of the second pointed observation of the HI hole were made. The laboratory calibration of the sensitivity, the in-flight subtraction of the instrumental offset, and the in-flight response calibration are described in Bock et al. (1993) and Kawada et al. (1994). The response of the spectrophotometer was monitored by an internal calibration lamp in flight, and was closely matched with the response observed in the laboratory. We estimate the uncertainty of the absolute brightness calibration to be 6.4% for the $152.5 \mu$m continuum, and 8.4% for the [C II] line.

As described in Bock et al. (1993), the [C II] line intensity is extracted from the difference between the LC and CC signals. Thus, the derived [C II] intensity depends on the spectral index $s (I, \propto v^s)$ of the continuum between 152 and

\(^2\) As a result of careful analysis of the spectral response of the spectrophotometer, the effective band-center wavelength ($\lambda_b$) and equivalent square bandwidth listed in Table 1 have been slightly corrected from those given in Table 2 of Matsuura et al. (1994) and Table 1 of Kawada et al. (1994). The differences are very small and do not affect any scientific results of previously published papers.

### TABLE 1

| Channel Name | CC     | LC     |
|--------------|--------|--------|
| $\lambda_{\text{peak}}$ (\(\mu\text{m}\)) | 152.43 | 157.66 |
| $\lambda_b$ (\(\mu\text{m}\)) | 152.54 | 157.75 |
| $\lambda_b/\Delta \lambda_b$ | 89.7 | 100.0 |
| Beam (FWHM) (arcmin) | 36 | 36 |

* Wavelengths at peak responses.

** Effective band-center wavelength ($\lambda_b$) and equivalent square bandwidth for $I \propto v^{-\kappa} (\Delta \lambda)$. 
The molecular clouds coincide with H I clouds emitting a comparable [C II] line and FIR continuum. Hence, in order to determine the [C II] and FIR continuum intensities emitted from the molecular clouds alone, we must estimate the contributions made by the H I and background components to the observed [C II] and continuum emissions. As shown in § 3.2, appreciable CO emission is found only for beams with $N_{\text{HI}} > 2 \times 10^{20}$ cm$^{-2}$. Thus we assume that all data with $N_{\text{HI}} < 2 \times 10^{20}$ cm$^{-2}$ do not have appreciable CO emission, and bin these $N_{\text{HI}}$ data in 0.1 ~ 0.2 x 10$^{20}$ cm$^{-2}$ intervals. Several beams (1, 2, 4, 5, 6, 7, 15, and 16) are also noted that have $N_{\text{HI}} > 2 \times 10^{20}$ cm$^{-2}$ but lack appreciable CO emission. These results are shown in Figure 2.

3. MILLIMETER $^{12}$CO OBSERVATION AND RESULTS

3.1. Observation

We use the millimeter-wave $^{12}$CO emission data to distinguish regions with significant molecular hydrogen. However, the beam positions of the rocket-borne instrument are not fully mapped by VHT. Thus, in order to increase the number of beams with $^{12}$CO data, we have observed at eight beam positions along the rocket observation path (labeled in Figure 1) with the Nagoya University 4 m millimeter telescope (Fukui & Sakakibara 1992) during 1994 February–March. Among these, beams 7, 8, and 9 were also mapped by VHT.

Because the beam of the rocket observation (36' in diameter) is much larger than that of the millimeter CO observations (2'), we mapped each beam position over a 40' x 40' or wider area. The mapping grid sizes were 4' ~ 5.66, except over parts of beams 5, 8, and 9, where a further 5 x 5 map was made around the emission peak with a 2' grid. Integration time per grid point was 3~6 minutes, with typical rms noise of 0.3 K per spectral channel (0.1 km s$^{-1}$). We used a frequency-switching method to obtain the line signal without observing a spatial reference point. Typically, data at $v < -4$ km s$^{-1}$ and $v > 10$ km s$^{-1}$ were used as the baseline for the $^{12}$CO line spectrum. We frequently observed Orion A for brightness calibration, assuming its brightness temperature to be 60 K. We also frequently observed the peak brightness position in beam 9 to correct for the effect of varying airmass, which we found to be negligible.

3.2. Results

We obtained a positive CO detection in 5 beams (3, 4, 5, 8, and 9), all of which have relatively large $N_{\text{HI}} (> 2 \times 10^{20}$ cm$^{-2}$). Contour maps of the velocity-integrated brightness temperatures of the CO line ($W_{\text{CO}}$ in K km s$^{-1}$) of these beams are shown in Figure 3, superposed on 100 $\mu$m maps reproduced from the IRAS Sky Survey Atlas (ISSA) by reducing the intensity by a factor of 0.72, following the COBE/DIRBE calibration (Wheelock et al. 1994). The spatial distribution of the integrated CO line in beams 8 and 9 (Figs. 3d and 3e) are in good agreement with those of VHT. However, we find that the absolute brightness temperature of VHT is systematically lower by a factor of 0.68. Since the purpose of the CO observations in this work is to supplement the observations of VHT, we scaled the brightness temperature of all data so that our data for beams 8 and 9 match the data of VHT.

We discovered a few isolated, small CO cloudbots in beams 3, 4, and 5. The typical spectra of the CO cloudbots are shown in Figure 4. The spectral data are integrated in

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**Figure 2.** (a) 152.5 $\mu$m continuum intensity vs. atomic hydrogen column density ($N_{\text{HI}}$); (b) [C II] 158 $\mu$m line intensity vs. $N_{\text{HI}}$. For most of the beam positions with $N_{\text{HI}} < 2 \times 10^{20}$ cm$^{-2}$, no CO data are available. From the correlation over beams with $N_{\text{HI}} < 2 \times 10^{20}$ cm$^{-2}$ and beams where there is no significant CO emission (beams 2, 4, 5, 6, 7, 15, and 16, where $W_{\text{CO}} < 0.2$ K km s$^{-1}$), we obtain the average FIR continuum emissivity and the [C II] cooling rate of the H I regions (solid lines).

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158 $\mu$m, and we have previously assumed $s = -1$. In Kawada et al. (1994), we reported the FIR continuum spectra of the observed regions using broadband photometer data. We derive $s = -0.25$ for the spectrum at the H I hole and $s = -0.65$ for the spectrum of a bright IR cirrus. We find that in the worst case, the assumption of $s = -1$ leads to a 10% systematic error in the [C II] intensity, so in this paper we use $s = -0.5$. The statistical error is derived from data obtained during the pointed observation of the H I hole between 310 s and 357 s after launch, as in Kawada et al. (1994): 0.7 pW cm$^{-2}$ sr$^{-1}$ for CC and 0.8 pW cm$^{-2}$ sr$^{-1}$ for LC, respectively. The 3 $\sigma$ [C II] line detection limit is estimated to be $2.7 \times 10^{-7}$ ergs s$^{-1}$ cm$^{-2}$ sr$^{-1}$.

We compare the resulting [C II] and 152.5 $\mu$m continuum data with the H I data (Heiles 1992, private communication) and the CO data of VHT. After the work of Bock et al. (1993), we determined the position of the telescope more accurately ($\pm 3'$) using near-infrared spectrometer data (Matsuura et al. 1994; Matsuhara et al. 1994). We find that the assumed pointing data used in Bock et al. (1993) were systematically offset by $\sim 8'$, so we resampled the H I data and the CO data, as we did in Kawada et al. (1994). The pointing correction is significant for the CO data, since the size of the CO clouds is generally smaller than the 36' beam.
Fig. 3. $^{12}$CO $J = 1 \rightarrow 0$ contour maps obtained with the 4 m millimeter telescope at Nagoya University, superposed on IRAS 100 $\mu$m maps. Eight beams (filled circles in Fig. 1) were surveyed for CO emission (typically $40' \times 40'$, $2' \times 2'$ grids) with positive detection for the five beams shown here. The contours are spaced at $\Delta W_{\text{CO}} = 0.6$ K km s$^{-1}$ for beams 3, 8, and 9 and 0.4 K km s$^{-1}$ for beams 4 and 5. The lowest contour level is 0.6 K km s$^{-1}$.

1 km s$^{-1}$ bins and fitted by a gaussian in order to evaluate the line widths. Location, size, line width, and the derived physical properties (details are described in § 4.3) of the cloudlets are listed in Table 2.

For comparison with the rocket-borne data, an average $W_{\text{CO}}$ was calculated by convolving the CO data with the 36$'$ beam of the rocket-borne instrument. Although we have a positive CO detection in beams 4 and 5, these cloudlets are
very small compared with the rocket beam and thus when averaged over the 36' beam do not give an appreciable average $W_{\text{CO}}$ (more than 3 $\sigma$, $\sim 0.2$ K km s$^{-1}$) for these beams. In the averaging procedure, the error is dominated by the poor quality of the spectral baselines incurred at some grid positions due to temporal changes in weather conditions during the observation. Only for beams 3, 8, and 9 did we obtain an appreciable $W_{\text{CO}}$ (>0.2 K km s$^{-1}$).

4. DISCUSSION

4.1. H I Regions

In previously published papers (Bock et al. 1993; Kawada et al. 1994), we assumed that there were no molecular regions except those mapped by VHT. Outside of the regions mapped by VHT, only beam 3 has appreciable CO emission. Therefore, the previous results for the physical properties of the H I regions do not change significantly. Here we summarize the results for the H I regions for the purpose of the following analysis of the molecular regions.

The correlation between 152.5 $\mu$m continuum emission and H I column density is shown in Figure 2a, and the correlation between [C II] emission and H I column density is shown in Figure 2b. The excellent correlation of 152.5 $\mu$m continuum intensity and H I column density strongly suggests that instrumental effects such as detector hysteresis are small. Laboratory data demonstrate that detector hysteresis is still further removed when the [C II] profile is derived from a difference of signals between two well-matched detectors.

The 152.5 $\mu$m continuum emissivity per H I column density is determined to be $\Delta I_\lambda/N_{\text{H I}} = 3.62 \pm 0.38 \times 10^{-32}$ W sr$^{-1}$, and the [C II] cooling rate per atomic hydrogen is determined to be $\Lambda_{\text{C II}} \equiv \chi_{\text{C II}} / N_{\text{H I}} = 1.32 \pm 0.04 \times 10^{-26}$ ergs s$^{-1}$ H$_{\text{atom}}^{-1}$. This value is in good agreement with the average cooling rate at high latitudes obtained by recent analysis of the COBE/FIRAS data, $\Lambda_{\text{C II}} = 1.45 \times 10^{-26}$ ergs s$^{-1}$ H$_{\text{atom}}^{-1}$ (Dwek et al. 1997). If only data with $N_{\text{H I}} < 2 \times 10^{20}$ cm$^{-2}$ are considered, these values change little: $\Delta I_\lambda/N_{\text{H I}} = 2.66 \pm 0.45 \times 10^{-32}$ W sr$^{-1}$, $\Lambda_{\text{C II}} = 1.64 \pm 0.39 \times 10^{-26}$ ergs s$^{-1}$ H$_{\text{atom}}^{-1}$. As already noted by Bock et al. (1993), inclusion of the region with a relatively low line-to-continuum ratio (beams 4, 5, 6, and 7) tends to increase the FIR continuum emissivity and decrease the [C II] line cooling rate. These uncertainties in $\Delta I_\lambda/N_{\text{H I}}$ and $\Lambda_{\text{C II}}$ for the H I-correlated components are, however, not significant in deriving the intensity of the [C II] line and FIR continuum from the molecular regions, and thus do not appreciably affect the following discussion.

4.2. The Conversion Factor $X = N(\text{H}_2)/W_{\text{CO}}$

We subtract the H I and background contributions from the 152.5 $\mu$m continuum and obtain the excess FIR emission plotted against $W_{\text{CO}}$ in Figure 5. The fitted line in Figure 5 gives $\Delta I_\lambda/W_{\text{CO}} = 8.6 \pm 2.1$ p W cm$^{-2}$ sr$^{-1}$ (K km s$^{-1}$)$^{-1}$, with no significant residual FIR emission at $W_{\text{CO}} = 0$. The conversion factor $X = N(\text{H}_2)/W_{\text{CO}}$, the parameter used to estimate the molecular column density over CO clouds, is derived assuming constant FIR emissivity per hydrogen nucleus in both the molecular and the H I regions. We find that $X = 1.19 \pm 0.29 \times 10^{20}$ cm$^{-2}$ (K km s$^{-1}$)$^{-1}$, not significantly different from the value derived by Kawada et al. (1994).

The conversion factor $X$ presumably is not constant, but varies significantly from region to region. VHT gives $X = 0.5 \pm 0.3 \times 10^{20}$ cm$^{-2}$ (K km s$^{-1}$)$^{-1}$ over a larger region of the molecular clouds using IRAS 100 $\mu$m data. We independently examine the factor $X$ on small scales by studying the correlation between CO and IRAS 100 $\mu$m emission for beams 3, 8, and 9, where CO counterparts are clearly visible in the IRAS 100 $\mu$m maps (Fig. 3). No correction for the H I component is applied to the IRAS 100 $\mu$m data, so significant spatial structure in H I column density invalidates this analysis. From the slopes of the fitted lines and the global FIR spectrum of dust emission ($\lambda I_\lambda(100 \mu$m)$/\lambda I_\lambda(100 \mu$m) = 1.5(+0.4, -0.3); Kawada et al. 1994), we derive the factor $X$ for beams 3, 8, and 9 as 0.54(+0.27,
density derived by dividing the column density of molecular hydrogen by the width of the CO filament (~1 pc in the plane of the sky) ranges from 10–50 cm⁻³, a value similar to that calculated by assuming a spherical cloud. It is interesting that the density of the small cloudlets in beams 3, 4, and 5 is much larger than that of the MBM clouds. This may suggest that the MBM clouds are very clumpy, consisting of smaller, denser cloudlets like those in beams 3, 4, and 5. Another interesting fact is that the average number density of these clouds is too low for CO molecules to survive the photodissociation rate from the interstellar UV field. For example, $n_\text{H}_2 R \sim 2 \times 10^{20}$ cm⁻², corresponding to $A_v \sim 0.1$ mag for CO 145.55+43.32 (the cloudburst in beam 3). Thus, to survive the photodissociation, the clouds may consist of many small and dense clumps. In which case, since we did not observe such clumpy structure with the 4 m telescope, each clump must be small enough to be unresolved (~2). Alternatively, the UV photons may be strongly attenuated by clouds intervening between the UV sources and the CO cloudlets (see § 4.4).

In Table 2, rough estimates of the turbulent pressure ($P_{\text{turb}}$) and the gravitational pressure ($P_{\text{grav}}$) are listed for the cloudlets in beams 3, 4, and 5, and for the MBM clouds. The turbulent pressure of the clouds is estimated from the $^{12}$CO velocity width ($\Delta V_{\text{FWHM}}$; see Fig. 4), the calculated mass $M$ of the cloud, and the effective radius $R$, using $4\pi R^2 P_{\text{turb}} = 3M\Delta V_{\text{FWHM}}^2/(8\ln2) R$. The gravitational pressure, calculated as $4\pi R^2 P_{\text{grav}} = 3GM^2/5R^2$, is orders of magnitude smaller than the turbulent pressure. Since the external thermal pressure of the H I gas (estimated by the [C ii] line cooling rate; see Bock et al. 1993), $\sim 10^{-13}$ ergs cm⁻³, is also much smaller than the turbulent pressure, the cloud cannot be bound by gravitation or by external thermal pressure. Joncas, Boulanger, & Dewdney (1992) calculated the magnetic pressure by using the magnetic field strength at $(l, b) = (142^\circ.6, 38^\circ.4)$ (close to beam 9) measured by Heiles (1989), and found it to be $1 \times 10^{-11}$ ergs cm⁻³. Joncas et al. (1992) also estimated the turbulent pressure of the H I gas to be $4 \times 10^{-11}$ ergs cm⁻³ from the velocity width of the H I emission line. Thus, as Joncas et al. (1992) concluded that for the H I clouds, the turbulent pressure in these molecular clouds is possibly balanced by the magnetic pressure as well as by the external turbulent pressure of the H I gas.

4.4. [C ii] Emission from the MBM Clouds

In Figure 6 we compare the spatial distribution of $W_{\text{CO}}$ and excess (i.e., corrected for H I and background

| Cloud          | $\alpha$ (1950) | $\delta$ (1950) | $\Delta v$ (km s⁻¹) | $R$ (pc) | $n_\text{H}_2$ (cm⁻³) | $P_{\text{grav}}$ (ergs cm⁻³) | $P_{\text{turb}}$ (ergs cm⁻³) |
|----------------|----------------|----------------|---------------------|---------|------------------------|-------------------------------|-------------------------------|
| CO 145.55+43.32 | 9h57m2          | 65°49'         | 2.1                 | 0.10    | 0.31                   | $2 \times 10^{12}$            | $7.2 \times 10^{12}$         |
| CO 145.04+42.30 | 9h50m8          | 66°42'         | 2.0                 | 0.009   | 0.10                   | $1 \times 10^{13}$            | $3.8 \times 10^{11}$         |
| CO 144.06+41.02 | 9h43m6          | 67°59'         | 2.4                 | 0.018   | 0.13                   | $1 \times 10^{12}$            | $6.9 \times 10^{12}$         |
| MBM clouds     |                |                | 2.9                 | 3.8     | 1.9                    | $32.4$                        | $2.5 \times 10^{12}$         |

* Typical observed line widths (in FWHM) of the CO emission.
  † Calculated using $R = (A/\pi)^{1/2} D$, where $A$ is area of the emission region, and $D$ is the distance to the source (assuming $D = 100$ pc).
  ‡ Calculated assuming $X \equiv N_\text{H}_2/W_\text{CO} = 1.2 \times 10^{20}$ cm⁻² (K km s⁻¹)⁻¹, mean molecular weight 1.4, and $D = 100$ pc.
  § Average volume density of molecular hydrogen assuming spherical volume of radius $R$.
  ¶ Gravitation pressure at radius $R$.
  ‡ Pressure at radius $R$ due to turbulent gas motion in the cloud (calculated from the velocity width).
  ‡ MBM 27, 28, 29, and 30 are labeled "CO 1" in Table 1 of VHT.
  ‡ Value in VHT is 13.3 $M_\odot$, using $X = 0.5 \times 10^{20}$ cm⁻² (K km s⁻¹)⁻¹.

Fig. 5.—Excess (corrected for H I and background contributions) 152.5 μm continuum emission vs. $W_{\text{CO}}$. The best linear fit is shown by a dashed line.
Fig. 6.—(a) Spatial distribution of $W_{\text{CO}}$ (filled triangles) and excess [C II] line intensity (filled circles) for beams 2–14, as shown in (b), representing a part of the observed region. The upper limits of $W_{\text{CO}}$ are $3\sigma$.

... contributions) [C II] line emission. Interestingly, the spatial distribution of the excess [C II] emission is very different from that of $W_{\text{CO}}$, while the 152.5 $\mu$m continuum emission does correlate with $W_{\text{CO}}$ (see Fig. 5). The [C II] emission peak is displaced from the CO peak toward lower latitudes by $\sim1^\circ$. In the following section, we discuss the origin of the excess [C II] emission and present the most plausible interpretation of this interesting behavior.

Excess [C II] emission could possibly originate from H II gas ionized by Lyman continuum photons or Galactic shock waves. One such ionized component of the local interstellar medium, the warm ionized medium (WIM), is responsible for diffuse Hz emission (see Reynolds 1993 and references therein). However, the Hz intensity over the entire observed region is unusually low [$I(\text{Hz}) \approx 0.7 \pm 0.5 \times 10^{-7}$ ergs s$^{-1}$ cm$^{-2}$ sr$^{-1}$; R. J. Reynolds 1996, private communication] compared to the average Hz intensity for $|b| \leq 15^\circ$, $<I(\text{Hz})> \approx 2.9 \times 10^{-7}$ csc $|b|$ ergs s$^{-1}$ cm$^{-2}$ sr$^{-1}$ (see eq. [8] of Reynolds 1992). In the low-density limit, the [C II] line intensity is proportional to the emission measure and hence proportional to the Hz intensity, $I(\text{C II}) \approx 1.45I(\text{Hz})$ for $T = 10^4$ K and C$^+$/H = $3.3 \times 10^{-4}$ (eq. [6] of Reynolds 1992). Thus we conclude that [C II] emission associated with the WIM is negligible, $I(\text{C II}) \leq 2 \times 10^{-7}$ ergs s$^{-1}$ cm$^{-2}$ sr$^{-1}$.

The excess [C II] emission may originate from shock-compressed H I gas, since the MBM clouds are located in the north celestial loop, a large (~20°) loop of H I gas produced by stellar winds or supernovae explosions (Heiles & Habeing 1974). Since [C II] emission is a collisionally excited line, the emission from shock-compressed (or shock-heated) H I gas is stronger than the emission from ambient low-density H I gas. In order to explain the observed [C II] strength of beams 10–14, for example, a few times higher density than that of the ambient H I gas is required. We think that this is quite unlikely, because beams 8, 9, 15, and 16, located on local maxima of the H I loop structure, show less [C II] emission than beams 10–14.

We propose that the excess [C II] emission originates from PDRs formed around molecular clouds, where CO molecules are photodissociated by FUV photons to produce C$^+$ ions (and C$^+$), while most of the hydrogen remains in molecular form (van Dishoeck & Black 1988; Hollenbach et al. 1991). At the surface of a PDR, [C II] 158 $\mu$m line emission dominates the gas cooling, while grain photoelectric heating is dominant over almost the entire PDR. Therefore, the spatial variation of [C II] emission should match the variation of the grain photoelectric heating. According to the models of Hollenbach et al. (1991) and Wolfire et al. (1995), the efficiency of grain photoelectric heating is almost constant where $G_0 \sim 1$, $n$(H$_2$) $\sim 20$ cm$^{-3}$ (the average density of the MBM clouds, Table 2), and $T \sim 100$ K. Thus, the variation of the grain photoelectric heating rate must be due to variation of the dust-to-gas mass ratio or variation of the FUV field strength. Since the FIR continuum emission is spatially well correlated with the CO emission, variation in the dust-to-gas mass ratio is unlikely, and variation of the FUV strength is most probable.

The variation of FUV strength can be explained by the location of a FUV source and the distribution of attenuating material. Because the MBM clouds are located about 60 pc above the Galactic plane (calculated from $D = 100$ pc and $b \approx 38^\circ$), cloud surfaces facing the Galactic plane are presumably illuminated by stronger FUV photons. Using the average density $n$(H$_2$) $\approx 20$ cm$^{-3}$ of the MBM clouds and the length of the molecular filament on the sky ($\sim 10$ pc), the optical depth through the excess [C II] emission region is estimated to be $A_V = 0.65$ mag or $A_{\text{FUV}} = 1.2$ mag ($A_{\text{FUV}}/A_V = 1.8$; De Jong, Dalgarno, & Boland 1980). The H I gas further contributes to the attenuation. Thus, FUV photons are significantly attenuated toward higher Galactic latitudes by the molecular and H I clouds, resulting in weaker [C II] emission. This might be the reason why the small CO cloudlets found at higher latitude regions (see §4.3) withstand photodissociation, and indeed why the [C II] line/FIR continuum ratio is anomalously low. The depth of the [C II] emission region agrees well with the theoretical thickness of the C$^+$ region formed on the surface of a molecular cloud illuminated by the standard interstellar FUV flux, $A_V$ (C$^+$) $\sim 0.5$ mag (van Dishoeck & Black 1988), further supporting this interpretation.

4.5. Overall Observational Properties of the MBM Clouds

The integrated FIR continuum intensity can be calculated from the observed 152.5 $\mu$m intensity, assuming the FIR spectrum determined by other photometric channels on the instrument ($T = 16.6$ K graybody, with an emissivity $\propto \lambda^{-2}$; Kawada et al. 1994). By averaging the [C II] intensity and the integrated FIR continuum intensity over the CO regions (beams 8–14), we obtain an average ratio of [C II]/FIR $\approx 0.0071$, close to the all-sky average of 0.0082 reported by FIRAS (Wright et al. 1991), which is heavily weighted toward the Galactic plane. Using the FIR continuum emissivity obtained for the H I clouds (§4.1), the observed [C II]/FIR ratio corresponds to a [C II] cooling rate of $\Lambda_{\text{C II}} \approx 3 \times 10^{-26}$ ergs s$^{-1}$ H$_{\text{nuc}}^{-1}$, a factor of two larger than that of the H I clouds. This may indicate that the heating efficiency is higher in the PDRs around the molecu-
lar clouds than in the diffuse H\textsc{i} clouds. We also obtain an average ratio of [C\textsc{ii}] / CO $\approx 420$ by taking the observed $W_{\text{CO}}$ and converting it to brightness by 1 K km s$^{-1} = 1.6 \times 10^{-9}$ ergs s$^{-1}$ cm$^{-2}$ sr$^{-1}$. This ratio is significantly smaller than that of molecular clouds in the Galactic plane (1500; Shibai et al. 1991), as expected if $G_0$ is lower at high Galactic latitude than in the Galactic plane (Hollenbach et al. 1991).

5. SUMMARY

We report the first [C\textsc{ii}] 158 $\mu$m line observation of high-latitude molecular clouds. The [C\textsc{ii}] line and 152.5 $\mu$m continuum data were obtained using a rocket-borne spectrophotometer observing a region at high Galactic latitudes in Ursa Major, including the MBM clouds. We also present the results of a follow-up observation of the millimeter 12 CO $J = 1 \rightarrow 0$ line.

Over the observed region, the ratio of molecular hydrogen column density to velocity-integrated CO intensity is $X = 1.19 \pm 0.29 \times 10^{20}$ cm$^{-2}$ (K km s$^{-1}$)$^{-1}$, assuming a constant FIR emissivity per hydrogen nucleus for both the molecular and the atomic regions. We have also discovered three small CO cloudlets as a result of the 12 CO observation of the selected region in Ursa Major. Using the factor $X$ and the observed width of the CO line, we estimate the mass and the turbulent pressure of the CO cloudlets. We find that these molecular cloudlets, as well as the MBM clouds, are not gravitationally bound. Magnetic pressure and turbulent pressure dominate the dynamic balance of the clouds.

After subtracting the H\textsc{i} and background contributions, we compare the spatial distributions of the [C\textsc{ii}] line, the 152.5 $\mu$m continuum, and the 12 CO line intensity. The [C\textsc{ii}] emission peak is displaced from the 12 CO line intensity peak, while the 152.5 $\mu$m continuum emission is spatially correlated with the 12 CO line emission. We discuss the origin of the [C\textsc{ii}] emission and conclude that the [C\textsc{ii}] emission most probably originates in PDRs around the molecular clouds illuminated by the local UV radiation field.

The average ratio of the [C\textsc{ii}] line to the integrated FIR continuum intensity over the MBM clouds was found to be 0.0071, which is close to the all-sky average of 0.0082 reported by FIRAS on COBE. This [C\textsc{ii}] / FIR ratio corresponds to the [C\textsc{ii}] cooling rate of $\Lambda_{\text{CII}} \approx 3 \times 10^{-26}$ ergs s$^{-1}$ H$^{-1}$, which is a factor of two larger than that of H\textsc{i} clouds. The [C\textsc{ii}] / CO ratio calculated in the same manner is 420, significantly lower than that of molecular clouds in the Galactic plane.

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SUMMARY

We find that these molecular cloudlets, as well as the MBM clouds, are not gravitationally bound. Magnetic pressure and turbulent pressure dominate the dynamic balance of the clouds.