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# MOLECULAR CLOUDS IN THE DWARF ELLIPTICAL GALAXY NGC 205

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## ABSTRACT

We present observations of CO emission in NGC 205 (a dwarf elliptical companion of M31) obtained with the Berkeley-Illinois-Maryland Association (BIMA) array and the IRAM 30 m telescope. We compare the CO results to VLA observations of the H I emission at the same spatial resolution. On scales of 90 pc, the atomic gas and dust have very similar distributions, and the atomic and molecular gas have similar kinematics. A $^{12}$CO (2–1)/(1–0) brightness temperature ratio of 0.9 is derived for one molecular cloud in NGC 205. This cloud is resolved by the 40 pc × 20 pc beam of the BIMA array; the cloud is elongated and shows a velocity gradient along its major axis. CO line widths are comparable to those in the Galaxy and the Small Magellanic Cloud (SMC) for clouds of the same size, which suggests that the molecular clouds in NGC 205 have similar virial masses to those in the Galaxy and the SMC.

*Subject headings:* galaxies: elliptical and lenticular, cD — galaxies: individual (NGC 205) — galaxies: ISM — Local Group — radio lines: galaxies

## 1. INTRODUCTION

In order to understand what determines the properties of the interstellar medium (ISM) and the relation of that ISM to star formation, it is important to observe the ISM in a variety of environments unlike our solar neighborhood. One example of an environment different from the solar neighborhood is the interior of the dwarf elliptical galaxy NGC 205, a companion of M31.

Though it is an elliptical, NGC 205 has long been classified as peculiar, because it has dust clouds and signs of recent star formation near its center (e.g., Hodge 1973; Peletier 1993). H I in NGC 205 was mapped at 1′ resolution by Johnson & Gottesman (1983), and a tentative detection of $^{12}$CO $J = 1-0$ emission in NGC 205 was reported by Sage & Wrobel (1989). Therefore, given the general deficiency of gas and star formation in elliptical galaxies (e.g., van Gorkom 1992), NGC 205 presents an excellent opportunity to study the properties of the interstellar medium at high spatial resolution in an unusual environment.

We have imaged the H I and CO emission in NGC 205 with a factor of more than 3 improvement in spatial resolution over the previous observations. We have partially mapped the CO (1–0) and CO (2–1) emission from dust clouds in NGC 205 with the IRAM 30 m telescope. We have also imaged its H I at 23″ resolution. At a distance of 0.85 ± 0.1 Mpc (Saha, Hoessel, & Krist 1992; Lee, Freedman, & Madore 1993), this resolution corresponds to 90 pc. We have imaged the CO (1–0) emission from one of the dust clouds in NGC 205 at 40 pc × 20 pc resolution using the new Berkeley-Illinois-Maryland Association (BIMA) nine-element array (Welch et al. 1996). In the present paper we discuss what these observations reveal about the properties of the ISM in NGC 205 and compare the molecular clouds in NGC 205 to their counterparts in our own spiral Galaxy and the SMC.

## 2. OBSERVATIONS

NGC 205 was observed in the $J = 1-0$ and 2–1 transitions of $^{12}$CO using the IRAM 30 m telescope on 1995 June 24–27. Four positions in NGC 205 were selected for study based on the presence of dust obscuration in optical images (Hodge 1973). The resolution of the 30 m telescope is 21″ at 115 GHz and 11″ at 230 GHz (Kramer & Wild 1994), comparable to the size of the larger optical dust clouds and to the resolution of our H I data. The telescope was operated in the wobbler switch mode with a throw of 180″ in azimuth. Integration times were typically 1–2 hr at each position. Baselines of order 0 and 1 were subtracted from the spectra. The spectra presented in this paper are in the main beam brightness temperature scale ($T_{\rm mb}$), which is related to antenna temperatures ($T_A^*$) by a factor of 1.37 at 115 GHz and 2.20 at 230 GHz (Guelin, Kramer, & Wild 1995). These observations and the others mentioned below will be described in more detail in a subsequent paper.

A portion of NGC 205 was observed in the $^{12}$CO 1–0 line with the BIMA millimeter-wave interferometer during 1995 October and December. We obtained a total of 33 hr of observation with six antennas and 16 hr with nine antennas. The primary beam of the BIMA array at 115 GHz is 2′ in diameter (FWHM), and the pointing center was chosen to be the location of the brightest CO emission in NGC 205 found in the 30 m observations. The resulting images have a 10″ × 5″ (40 pc × 20 pc) beam and an rms noise of 0.15 K in one 3 km s$^{-1}$ channel.

NGC 205 was also observed in the 21 cm line of H I, using the D and C configurations of the Very Large Array (VLA) of the NRAO[1] in 1994–1995. The galaxy was observed for 4 hr in the D configuration and 8 hr in the C configuration. The data

[1] The National Radio Astronomy Observatory is a facility of the National Science Foundation operated under cooperative agreement by Associated Universities, Inc.

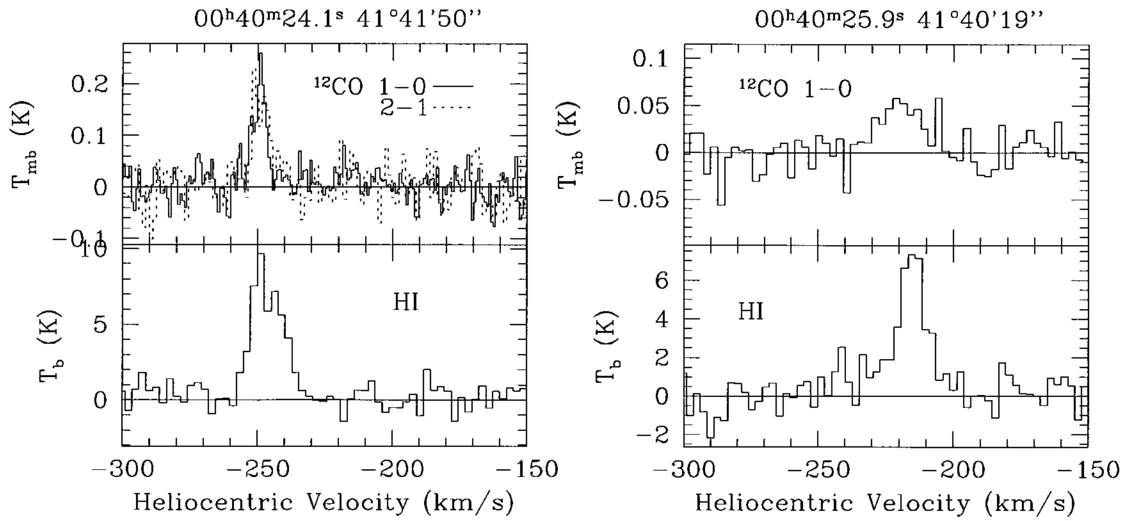


FIG. 2.—CO spectra from the 30 m telescope are compared to H I spectra. The H I spectra have a spatial resolution of 23″, similar to the 21″ of the 30 m $J = 1$–$0$ spectra. On the left, the spectra in the northern cloud are shown, and the $J = 2$–$1$ data have been smoothed to the same spatial resolution as the $J = 1$–$0$ data. The $J = 2$–$1$ transition was not detected at the position shown on the right.

were calibrated, imaged, and cleaned using standard data reduction routines in the Astronomical Image Processing System package. The final images have resolutions of 23″ and 2.6 km s$^{-1}$ and an rms noise level of 0.8 K.

## 3. RESULTS

### 3.1. *Distribution of ISM*

Figure 1 (Plate L9) shows a narrowband red optical image of NGC 205 (*gray scale*) along with the H I column density (*contours*), the locations that were searched for CO emission using the 30 m telescope (*triangles*), and the dust clouds in Hodge's (1973) Figure 22 (*irregular dark areas*). We detect a total of $4 \times 10^5$ $M_\odot$ of H I in NGC 205; all of the H I is found within about 3′, or 700 pc, of the optical center of the galaxy, though the optical galaxy itself is some 22′ across (RC3). The H I is distributed in an elongated, bent structure 900 pc long and 300 pc wide. The structure is clumpy on scales down to the size of the beam (90 pc) and shows peak H I column densities of $4 \times 10^{20}$ cm$^{-2}$ on that scale.

A detailed comparison of dust and H I in Figure 1 shows that the dust closely follows the elongated, bent H I structure in both shape and extent. In addition, $^{12}$CO emission was detected with the 30 m telescope toward two dust clouds in NGC 205 (Figs. 1 and 2). The northern-detected CO position is coincident with a local peak in the H I column density of $2.4 \times 10^{20}$ cm$^{-2}$ and diameter 150 pc. The southern-detected CO position is also near a local maximum in the H I column density of about $2 \times 10^{20}$ cm$^{-2}$.

The young stars in NGC 205 are concentrated within 30″ of the optical center of the galaxy (Peletier 1993). The highest concentration of these young stars is about 20″ northwest of the optical nucleus (Peletier 1993; Wilcots et al. 1990; Hodge 1973); this large clump of young stars is not coincident with any of Hodge's (1973) dust clouds or with any obvious peak in the H I column density (Fig. 1).

### 3.2. *Molecular Clouds*

Table 1 gives the Gaussian parameters and integrated intensities of the CO lines detected at the 30 m telescope. For the northern-detected CO cloud in NGC 205, a five-point map was made by observing four positions around the central position and offset by 10″. The results are consistent with a deconvolved source size of 13″, in good agreement with the BIMA image discussed below. The 2–1 line was then convolved to a resolution comparable to that of the 1–0 line. The widths of the 1–0 and 2–1 lines agree within the errors, and the

TABLE 1

FITTED PARAMETERS OF 30 m CO DETECTIONS IN NGC 205

| $\alpha$ (J2000) | $\delta$ (J2000) | Line | $T_{\rm mb}$ (K) | Center (km s$^{-1}$) | FWHM (km s$^{-1}$) | $\int T_{\rm mb}\,dV$ (K km s$^{-1}$) | (2–1)/(1–0) |
|---|---|---|---|---|---|---|---|
| 00$^h$40$^m$24.1$^s$............ | +41°41′50″ | 1–0 | 0.19 | $-249.6 \pm 0.3$ | $6.6 \pm 0.7$ | 1.44 | 0.92 |
| | | 2–1[a] | 0.14 | $-250.2 \pm 0.5$ | $8.5 \pm 1.2$ | 1.32 | ... |
| | | H I | 8.4 | $-246.7 \pm 0.3$ | $14.1 \pm 0.8$ | ... | ... |
| 00 40 25.9............ | +41 40 19 | 1–0 | 0.053 | $-218.8 \pm 1.8$ | $19.8 \pm 3.7$ | 1.0 | ... |
| | | 2–1 | <0.12[b] | ... | ... | ... | ... |
| | | H I | 7.1 | $-215.2 \pm 0.4$ | $12.8 \pm 0.9$ | ... | ... |
| 00 40 21.1............ | +41 41 13 | 1–0 | <0.067 | ... | ... | ... | ... |
| | | 2–1 | <0.16 | ... | ... | ... | ... |
| 00 40 21.6............ | +41 39 49 | 1–0 | <0.13 | ... | ... | ... | ... |
| | | 2–1 | <0.24 | ... | ... | ... | ... |

[a] Convolved to 21″ resolution.

[b] Upper limits are 3 $\sigma$ in one channel of 1.3 km s$^{-1}$ width ($J = 1$–$0$) or 2.6 km s$^{-1}$ width ($J = 2$–$1$).

ratio of the integrated line intensities (Table 1) is 0.92. The expected uncertainty in the line ratio is 20%, based on the calibration errors at the two frequencies.

Table 1 also compares the fitted parameters of the CO lines to those of the H I spectra at the same position and similar spatial resolution, 23″ (Fig. 2). H I and CO line centers differ by only 3.5 km $s^{-1}$. In the northern cloud, the H I width is larger than the CO width by a factor of 2, but in the southern cloud the H I width is 50% smaller than the CO width.

The CO emission from the northern dust cloud was also imaged at high spatial resolution using the BIMA array (Fig. 3 [Pl. L10]). The peak brightness temperature observed is 1.0 K, located less than 3″ from the central position used for the 30 m observations of this cloud and 7″ (30 pc) from the center of the nearby H I column density peak. CO emission is detected over a velocity range of 9 km $s^{-1}$, in agreement with the FWHM of 7 km $s^{-1}$ measured by the 30 m telescope. The emission is clearly elongated in a northwest-southeast direction with a major axis extent of 15″, and channel images show smaller clumps within this elongated structure. These high-resolution BIMA images also show that the cloud has a velocity gradient with a magnitude of 0.2 km $s^{-1}$ $pc^{-1}$ along the major axis, suggestive of rotation. Although Hodge's (1973) Figure 22 shows four additional compact dust clouds in the BIMA field of view, no emission is detected from them in the velocity range $-180$ to $-294$ km $s^{-1}$ at a 3 $\sigma$ level of 0.45 K (averaged over 40 pc × 20 pc).

## 4. DISCUSSION

### 4.1. *Properties of the ISM*

The dust clouds identified by Hodge (1973) have dimensions of 10–200 pc, and the CO emission in Figure 3 has a dimension of 15″, or 60 pc; therefore, the molecular clouds we are considering in NGC 205 are comparable to Galactic giant molecular clouds (GMCs) in terms of linear size. The observed peak CO brightness temperature in NGC 205 of 1.0 K places a lower limit on the CO excitation temperature of 4 K. Thus, the $^{12}$CO (2–1)/(1–0) line ratio of 0.92 for the northern cloud in NGC 205 is consistent with optically thick, thermalized CO emission. Typical values for the density and temperature might be $n_{H_2} \sim 10^2$–$10^3$ $cm^{-3}$ and $T \geq 10$ K, though of course they cannot be constrained with only one line ratio.

A "standard" $^{12}$CO (1–0) to $H_2$ conversion ratio of $2 \times 10^{20}$ $cm^{-2}$ (K km $s^{-1})^{-1}$ (Strong et al. 1988) gives $H_2$ column densities of (2–3) × $10^{20}$ $cm^{-2}$, averaged over 21″, for the two detected positions in NGC 205. These values are comparable to the peak H I column densities observed at the same spatial resolution. Furthermore, from the size of the northern molecular cloud (Fig. 3) and its line width of 6.6 ± 0.7 km $s^{-1}$ (Table 1), we estimate a virial mass $M_{vir} \leq 3 \times 10^5$ $M_\odot$.

The H I clump at the northern-detected CO position (Fig. 1) has a peak column density of about $2.4 \times 10^{20}$ $cm^{-2}$, which corresponds to an average volume density of 0.5 $cm^{-3}$ when averaged over 150 pc. The observed velocity dispersion of this H I constrains its spin temperature to be less than 4300 K; kinetic temperatures $\sim 10^3$ K would give approximate pressure equilibrium with the molecular gas described above. The size and line width of this H I clump give a virial mass of $M_{vir} \leq 3 \times 10^6$ $M_\odot$, whereas the total atomic mass of the clump is only $6 \times 10^4$ $M_\odot$ (after correcting for He). Clearly, this atomic cloud is not gravitationally bound, and it may not be bound to its associated molecular gas either.

### 4.2. *Association of Molecular and Atomic Gas*

The identification of individual H I clumps with CO emission and the agreement in H I and CO kinematics suggest a close association between the molecular and atomic gas in NGC 205. Since NGC 205 is known to contain some young massive stars, we investigate whether the atomic gas in the galaxy might simply be a photodissociated skin around the molecular clouds. If so, it would be a very thick skin (100 pc, based on the width of the H I distribution in Fig. 1).

From the number and approximate spectral type of the young massive stars in NGC 205 (Wilcots et al. 1990), and the fact that the highest concentration of those stars is in a clump about 20″ north and west of the nucleus, we estimate that the UV field at the position of the northern molecular cloud is about equal to the solar neighborhood interstellar radiation field (Draine 1978). Van Dishoeck & Black (1986) have shown that a cloud with a $H_2$ column density of $4 \times 10^{20}$ $cm^{-2}$, immersed in Draine's (1978) UV field, will have an atomic envelope of column density $4 \times 10^{20}$ $cm^{-2}$ if its central density is 200–300 $cm^{-3}$. This result is in rough agreement with the column densities observed in NGC 205 and with the fact that the CO emission appears to be thermalized. However, van Dishoeck & Black (1986) also show that the column density of H I surrounding a molecular cloud should be approximately proportional to the UV field. In NGC 205 we do not observe a decrease in H I column density with projected distance from the prominent clump of young massive stars.

If H I surrounds a molecular cloud immersed in the UV field of the young stars in NGC 205, the H I might be expected to have a higher temperature and a larger line width than the CO. This expectation clearly holds for the northern-detected CO position but not for the southern one, which has a larger CO width than H I width. Perhaps there is some internal source of kinetic energy, such as current star formation and molecular outflows, stirring up the molecular gas at the southern cloud. Unfortunately, the UV image of Peletier (1993) is not large enough to reveal whether there are young massive stars near the southern-detected CO position.

### 4.3. *Comparison of* CO *in NGC 205 to the Galaxy, the SMC, and M31*

The resolution of the 30 m $J = 1-0$ data in NGC 205 is 90 pc, and on these size scales, Rubio et al. (1993b) show Galactic and SMC 1–0 line widths (FWHM) varying between 3 and 16 km $s^{-1}$. Line widths in NGC 205 are 7 and 20 km $s^{-1}$. We infer that the molecular clouds in NGC 205 probably have similar virial masses to the clouds in the Galaxy and the SMC.

The peak brightness temperature of CO emission observed in NGC 205 (1.0 K) is low relative to the expected gas kinetic temperature and is comparable to brightness temperatures observed in the SMC and M31 on similar spatial scales (Rubio et al. 1993a; Allen & Lequeux 1993). In the nucleus of M31, Allen & Lequeux (1993) attribute low brightness temperatures to subthermal excitation, because they found (2–1)/(1–0) line ratios of less than 0.5. However, this explanation probably does not work for NGC 205, because of its higher line ratio.

If the (2–1)/(1–0) line ratio of 0.9 in NGC 205 indicates optically thick, thermally excited emission, then the low brightness temperatures must be due to a small beam filling factor of only a few percent. Rubio et al. (1993b) also interpret low CO brightness temperatures in the SMC as being due to a very small beam filling factor, presumably the result of the low metallicity and high UV field in the SMC. However, the metallicity of NGC 205 (0.5 times solar; Richer & McCall 1995) is higher than in the SMC, and the UV field in NGC 205 is comparable to that in the solar neighborhood (§ 4.2).

### 4.4. *Star Formation and the ISM*

The CO-to-$H_2$ conversion factor mentioned in § 4.1 gives as a lower limit on the total molecular gas mass in NGC 205 $9 \times 10^4\ M_\odot$, including helium. (The lower limit arises primarily because we have not observed the entire galaxy.) Thus, the molecular gas mass is probably somewhat smaller than the atomic gas mass of $6 \times 10^5\ M_\odot$ (including He). The dust mass estimated by Fich & Hodge (1993) is $\geq 1300\ M_\odot$.

In comparison, the total mass of young ($\sim 10^7$ yr old) stars in NGC 205 has been variously estimated at a few times $10^5$ to a few times $10^6\ M_\odot$ (Wilcots et al. 1990; Hodge 1973). If these estimates are correct, the mass of young stars in NGC 205 is close to the total amount of neutral ISM present in the galaxy. The mass of young stars is especially high if we consider that star formation is usually inefficient at converting gas to stars, so that $10^5$–$10^6\ M_\odot$ of young stars probably required a $10^6$–$10^7\ M_\odot$ of neutral gas just $10^7$ yr ago. That amount of neutral gas is not present in NGC 205 today. We suggest either that the estimates of the mass of young stars in NGC 205 are too high by about a factor of 10 or that the recent episode of star formation in NGC 205 was unusually efficient in using or destroying neutral gas, or that most of the molecular gas in NGC 205 has not yet been detected.

## 5. SUMMARY

The H I in the dwarf elliptical galaxy NGC 205 is distributed in an elongated, bent structure 900 pc long and 300 pc wide. We find close agreement between the distributions of atomic gas and dust and between the kinematics of atomic and molecular gas at resolutions of 90 pc, suggesting a close physical association between the atomic and molecular gas. A $^{12}$CO (2–1)/(1–0) line ratio of 0.9 is measured for one molecular cloud in NGC 205; this cloud is elongated, with a dimension of 15″ northeast-southwest, and it appears to be rotating. The CO line ratio, line widths, and cloud sizes suggest that the molecular gas in NGC 205 has similar properties to that in the Galaxy and the SMC.

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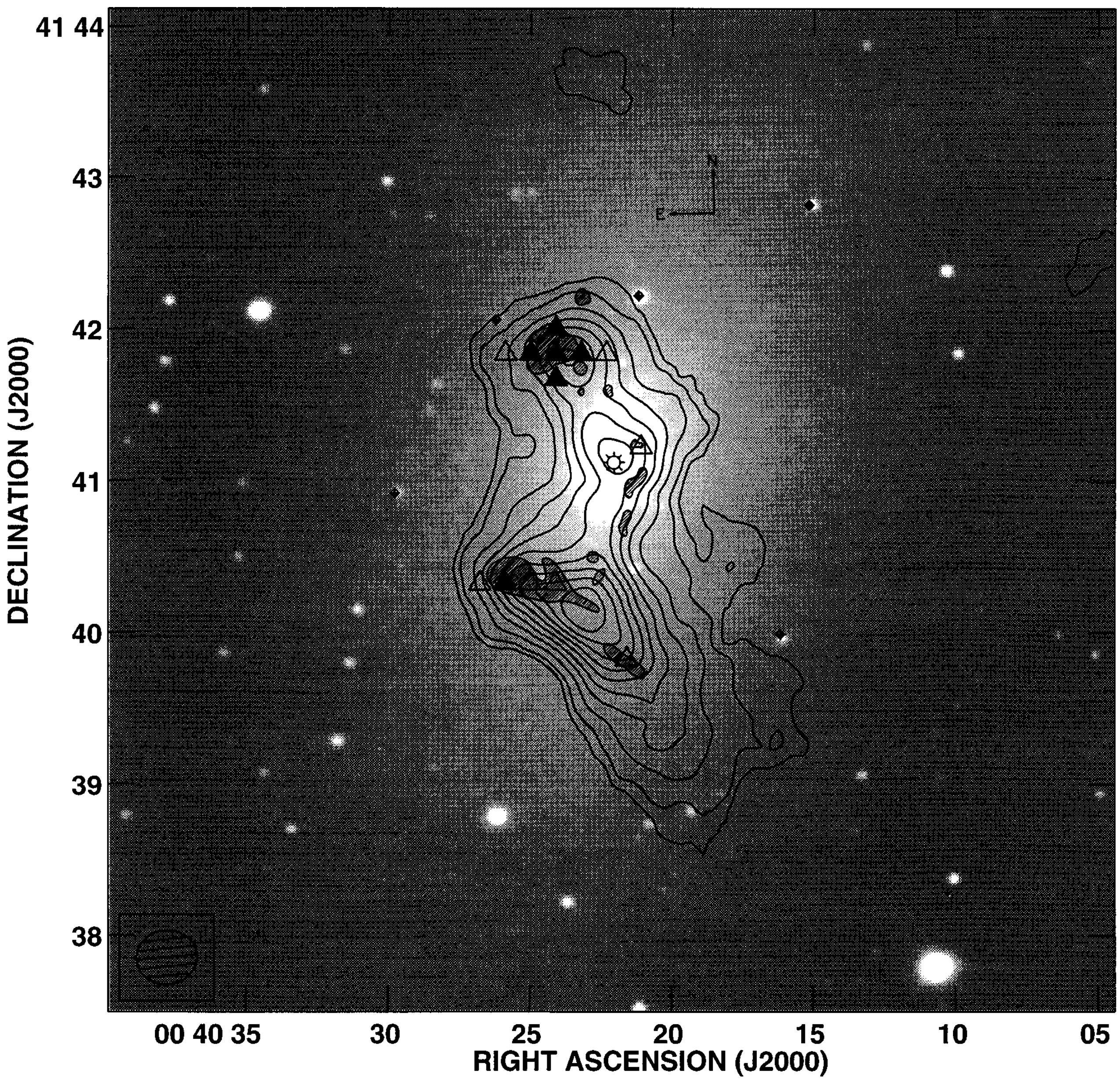


FIG. 1.—Gray scale is an optical image of NGC 205; it was obtained at the 1 m telescope of Mount Laguna Observatory in 1994 October as part of a search for H$\alpha$ emission. This image was taken through the H$\alpha$ + red continuum filter. The coordinate system in this image was determined to an accuracy of better than 1″ using 13 stars from the APM catalog. The contours show H I column density, which peaks at $4.0 \times 10^{20}$ cm$^{-2}$ (over 23″); contour levels are 5%, 10%, 20%, 30%, 40%, 50%, 60%, 70%, 80%, and 90% of the peak. The H I resolution is shown in the lower left corner. Filled triangles mark positions where CO emission was detected at the 30 m telescope; open triangles mark positions where CO was not detected. The irregular dark areas illustrate the distribution of dust in NGC 205 as reproduced from Hodge's (1973) Fig. 22.

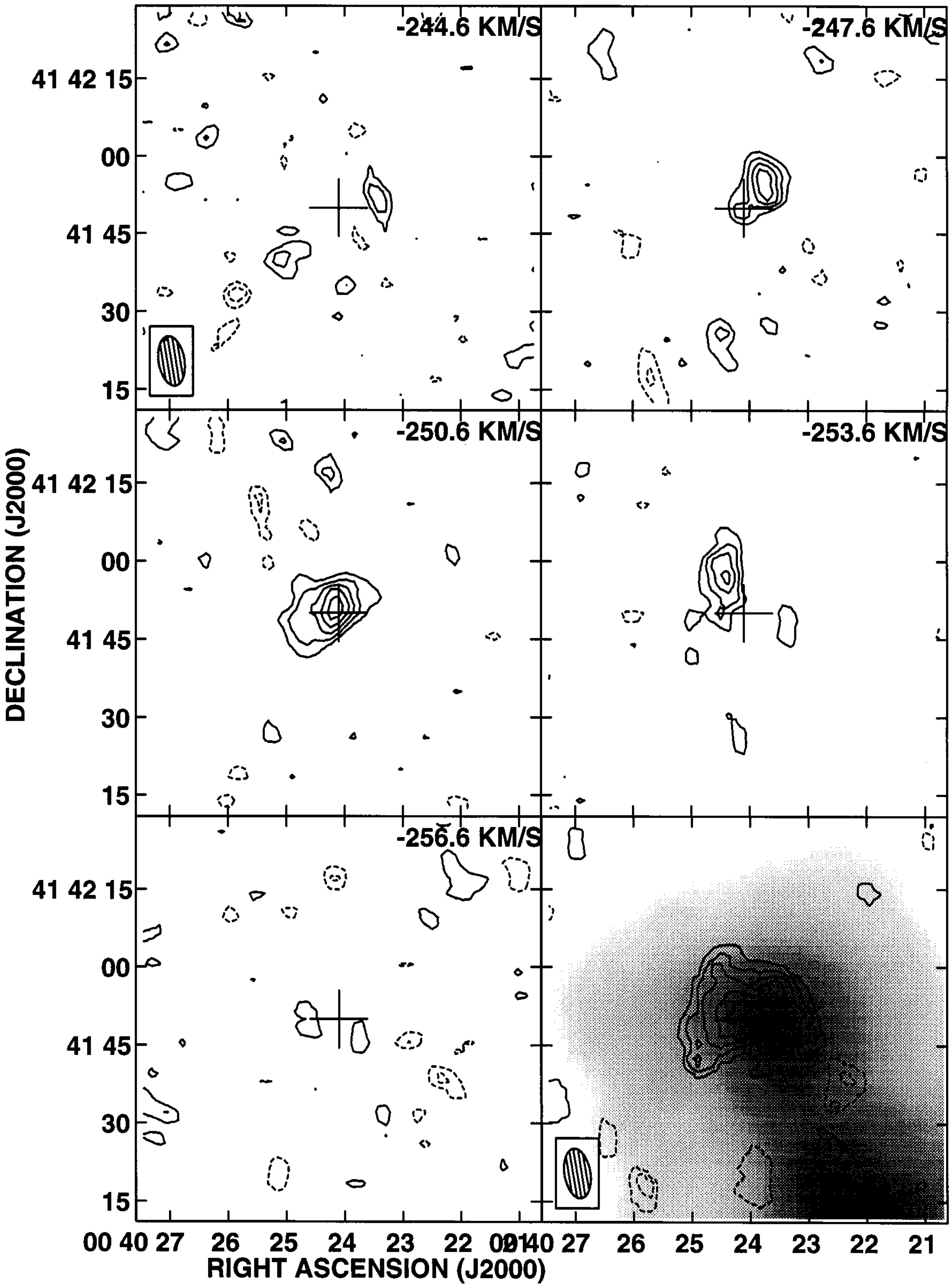


FIG. 3.—Channel maps made with the BIMA array and showing the northern molecular cloud in NGC 205. The contour levels are −3, −2, 2, 3, 4, 5, and 6 times the rms noise (0.15 K). The heliocentric velocity of each channel is marked, and the resolution is shown in the lower left corner. The cross marks the peak position and beam size of the 30 m $J = 2$–1 observations. The last panel shows the integrated CO intensity (*contours*) superposed on the H I column density (*gray scale*); for this panel, the contours are −30%, −10%, 10%, 30%, 50%, 70%, and 90% of the peak (5.6 K km $s^{-1}$).

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