DISCOVERY OF HIGH-LATITUDE CO IN AN H I SUPERSHELL IN NGC 5775

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ABSTRACT

We report the discovery of very high latitude molecular gas in the edge-on spiral galaxy NGC 5775. Emission from both the $J = 1-0$ and 2–1 lines of $^{12}$CO is detected up to 4.8 kpc away from the midplane of the galaxy. NGC 5775 is known to host a number of $\text{H} \, \text{I}$ supershells. The association of the molecular gas ($M_{\text{H}_2} \, \text{F}_2 = 3.1 \times 10^7 \, M_{\odot}$) reported here with one of the $\text{H} \, \text{I}$ supershells (labeled F2) is clear, which suggests that molecular gas may have survived the process that originally formed the supershell. Alternatively, part of the gas could have been formed in situ at high latitude from shock compression of preexisting $\text{H} \, \text{I}$ gas. The CO $J = 2-1/J = 1-0$ line ratio of $0.34 \pm 0.04$ is significantly lower than unity, which suggests that the gas is excited subthermally, with gas density a few times $10^2 \, \text{cm}^{-3}$. The molecular gas is likely in the form of cloudlets that are confined by magnetic and cosmic-ray pressure. The potential energy of the gas at high latitude is found to be $2 \times 10^{46} \, \text{ergs}$, and the total ($\text{H} \, \text{I} + \text{H}_2$) kinetic energy is $9 \times 10^{53} \, \text{ergs}$. Based on the energetics of the supershell, we suggest that most of the energy in the supershell is in the form of potential energy and that the supershell is on the verge of falling and returning the gas to the disk of the galaxy.

Subject headings: galaxies: halos — galaxies: individual (NGC 5775) — galaxies: ISM — galaxies: spiral — ISM: bubbles

1. INTRODUCTION

Galactic $H \, I$ shells and supershells, distinguished by whether their initial energy requirement is less or more than $10^{53} \, \text{ergs}$, were first studied by Heiles (1979, 1984). The large energies found in the supershells ($\approx 10^{53} \, \text{ergs}$) imply that these structures must have a tremendous influence on the structure of the interstellar medium. In addition, supershells that break through the gaseous disk to reach high Galactic latitudes may be a source of star formation in the halo. For example, supershells may act as “chimneys” through which hot gas from the disk funnels to the halo (e.g., the “chimney model;” Norman & Ikeuchi 1989). This hot gas may cool and eventually form stars in the halo. Alternatively, the molecular gas in the supershell may reach high latitude and directly provide raw material for star formation in the halo. Although which of these two scenarios is at work cannot be distinguished easily, the study of molecular gas in supershells still provides an important clue to high-latitude star formation. Molecular gas at high latitude also presents an important aspect in the understanding of the global evolution of the interstellar medium in spiral galaxies. In the Milky Way, the study of supershells is hindered by difficulties with distance determination and the resulting confusion. In external galaxies, these problems are minimized.

NGC 5775 is an edge-on ($i = 86^\circ$), infrared-bright ($L_{\text{IR}} = 2.6 \times 10^{10} \, L_\odot$) galaxy at a distance of 24.8 Mpc. Irwin (1994) observed this galaxy and its face-on neighbor, NGC 5774, in $\text{H} \, \text{I}$ using the Very Large Array and provided models for their $\text{H} \, \text{I}$ distributions. She showed that the two galaxies may be engaging in an early phase of interaction, with two $\text{H} \, \text{I}$ bridges connecting them. Numerous $\text{H} \, \text{I}$ arcs and extensions beyond the disk of NGC 5775 are also observed. Six $\text{H} \, \text{I}$ supershells were cataloged by Lee (1998). In a multiwavelength study of NGC 5775, Lee et al. (2001) report spatial correlations of $\text{H} \, \text{I}$, radio continuum, X-rays, and far-infrared emission at the positions of the three largest $\text{H} \, \text{I}$ supershells, labeled F1 through F3 in Figure 1.

2. OBSERVATIONS

Observations were performed with the IRAM 30 m telescope in 2000 October and 2001 April and November. The CO $J = 1-0$ line at 115 GHz and the $J = 2-1$ line at 230 GHz were observed simultaneously using two dual mixers tuned in single-sideband mode. The observations were done in “wobbler” switching mode with a wobbler throw of 240", resulting in very flat baselines. Relevant observing and spectral parameters are listed in Table 1. Data reduction was carried out using the GILDAS software package. Gaussian fits were obtained in order to find the peak antenna temperatures, central velocities, FWHMs, and the integrated intensities of the lines. For clarity of presentation, we define the $x$- and $y$-directions to be parallel and perpendicular to the galaxy’s major axis, respectively. All offsets are given in the form ($x$-offset, $y$-offset) in units of arcseconds, where the offsets are measured with respect to the reference.
Fig. 1.—H\textsubscript{i} column density contours superposed on the Digitized Sky Survey image of the vicinity of NGC 5775. The white crosses indicate the centers of NGC 5775 (left center), NGC 5774 (upper right), and IC 1070 (bottom). Contour levels are at 1, 5, 10, 17.5, 25, 40, 60, and 100 cm\textsuperscript{-2}. The H\textsubscript{i} supershells are labeled F1–F3.

TABLE 1

| Parameter | 115 GHz | 230 GHz |
|-----------|---------|---------|
| $T_{\text{sys}}$ (K) | 250 | 350 |
| HPBW (arcsec) | 21 | 11 |
| $B_{\text{eff}}$ | 0.75 | 0.52 |
| $F_{\text{eff}}$ | 0.95 | 0.91 |
| Channel width (km s\textsuperscript{-1}) | 26 | 21 |
| Spectra rms (mK) | 2 | 3 |

* Typical system temperature.
* Main-beam efficiency.
* Forward efficiency.

We initially searched for CO emission at a few selected positions in all three H\textsubscript{i} supershells (see Fig. 1). Although all three showed tentative detections, the spectral lines at F2 are the most obvious. We therefore proceeded to map the CO emission in F2. The observed $^{12}$CO $J = 1$–0 and $J = 2$–1 spectra are presented in Figure 2, superposed on the H\textsubscript{i} total intensity map. Emission from both CO transitions is detected up to 400" (4.8 kpc) away from the midplane of the galaxy. Within the region (35, -25) to (60, -40), roughly the size of the CO $J = 1$–0 beam, the average peak values of $T_{\text{MB}}$ for CO $J = 1$–0 and 2–1 are about 13 mK (3.2 $\sigma$) and 13.5 mK (2.3 $\sigma$), respectively. The fact that there is an absence of CO emission near the H\textsubscript{i} “hole” at the offset of (55, -30) (see Fig. 2) suggests that the molecular gas mimics the shell-like distribution of the H\textsubscript{i} feature F2.

Emission from a flared or warped disk may resemble gas at high latitude when seen in projection. However, in such a case the line-of-sight central velocity of the emission line, which presumably originates from the outer part of the disk, would be much closer to the systemic velocity of the galaxy. We therefore compare the average central velocity and average FWHM of all CO (1–0) spectra in F2 to a spectrum along the major axis. The average central velocity and average FWHM at F2 are 131 ± 19 and 83 ± 23 km s\textsuperscript{-1}, respectively. The uncertainties are the standard deviations of all the spectra and are both smaller than the velocity resolution. At (40, 0) (spectrum not shown), the corresponding values are 126 and 69 km s\textsuperscript{-1}, respectively. The central velocity comparison shows that the gas in F2 shares the same circular velocity as the major-axis gas at the same Galactocentric distance and does not originate from the outer disk. The narrow line widths support this, since gas from the outer disk would have wider spectra. Therefore, we conclude that the...
gas associated with F2 is indeed at high Galactic latitude and not from a flared or warped disk. Detailed analysis of the kinematic structures of the galaxy and the supershell will be forthcoming.

In order to study the molecular gas that truly belongs to the supershell at high latitude, we have to eliminate the contribution of CO from the disk. We assume that the vertical CO distribution of the galaxy can be represented by a single Gaussian that peaks at the midplane and that the emission from the supershell at high latitude is superposed on the wing of the Gaussian. The emission from the supershell can then be isolated by subtracting the Gaussian model from the observed data. To fit the Gaussian, we average the CO integrated intensity map from $\pm 20''$ to $-20''$ (hence, it does not include the high-latitude emission). The results of the fits are good, the residuals being less than 5% of the peak values in both transitions. At the center of the supershell ($y$-offset $= -32.5''$), the difference in integrated intensities between the data and the model gives the CO emission from the supershell alone. The total (disk contribution plus supershell contribution) integrated intensities within a $21''$ beam at the center of F2 are 1.28 and 1.05 K km s$^{-1}$ for the 1–0 and 2–1 transitions, respectively, where the temperatures are in the $T_{\text{mb}}$ scale. The uncertainties in these values, taking into account noise, calibration, and baseline errors, are about 30%. For proper comparison, the CO $J = 2–1$ data were smoothed to the resolution of the 1–0 data. After subtracting the disk contribution, the CO (1–0) and (2–1) integrated intensities are given by $I_{\text{1-0}} = 0.89$ K km s$^{-1}$ and $I_{\text{2-1}} = 0.30$ K km s$^{-1}$, respectively. The line ratio of the two transitions, $I_{\text{2-1}}/I_{\text{1-0}}$, is therefore 0.34 ± 40%.

For comparison, we obtained the line ratio at midplane corresponding to the same galactocentric radius of F2. We use our James Clerk Maxwell Telescope (JCMT) CO $J = 2–1$ integrated intensity ($=17.4 \pm 20\%$ K km s$^{-1}$) at the position equivalent to (40, 0) (Lee 1998) and the IRAM 30 m CO $J = 1–0$ integrated intensity ($=20.2 \pm 20\%$ K km s$^{-1}$) at the same position. The JCMT beam has the same half-power beamwidth (HPBW) as the IRAM 30 m beam at these frequencies. The resultant line ratio at the midplane is 0.86 ± 30%.

The total molecular gas mass in F2 (excluding the disk contribution), obtained using the CO $J = 1–0$ integrated intensity, is found to be $M_{\text{H}_2,F2} = 3.1 \times 10^7 M_\odot$ within the $21''$ beam ($\approx 2.5$ kpc in diameter), assuming a CO-H$_2$ conversion factor of $3 \times 10^{20}$ cm$^{-2}$ K km s$^{-1}$ (Young & Scoville 1991). Since the CO and the H i distributions within F2 agree fairly well, we have probably detected most of the CO emission in the supershell (see Fig. 2).

We have also obtained the H i integrated intensity within a $21''$ beam at F2 following the same procedure outlined above. The H i data have been published in Irwin (1994) and in Lee et al. (2001). The H i integrated intensity, after subtracting the disk contribution, is 0.11 Jy beam$^{-1}$ km s$^{-1}$, and the corresponding H i mass is $M_{\text{H}_i,F2} = 1.6 \times 10^7 M_\odot$, or 50% of $M_{\text{H}_2,F2}$. The total gas mass ($\text{H i} + \text{H}_2$) in F2 is therefore $4.7 \times 10^7 M_\odot$.

4. DISCUSSION

This Letter reports the highest latitude (4.8 kpc) molecular gas detected to date in any galaxy. In our own Galaxy, high-latitude molecular clouds are found in association with the H i shells around two OB associations—the Per OB3 and the Sco OB2 associations (Bhatt 2000)—and in association with a hot bubble between Cepheus and Cassiopeia (Grenier et al. 1989).

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4.1. Physical Conditions in the Supershell

The line ratio (0.34 ± 40%) for the extraplanar gas obtained is significantly lower than the corresponding ratio at the midplane. Even taking into account the uncertainty, its highest possible value is less than 0.5. Assuming that the gas is thermalized so that the excitation temperature of all rotational levels is the same, the interpretation of such a low line ratio is that the excitation temperature is low ($T_{\text{ex}} \approx 5$ K). Although no estimate of the gas or dust temperature in the supershell is currently known, the possibility of shocks, deduced from the trend of radio continuum spectral indices (see Lee et al. 2001), suggests that the gas kinetic temperature may be greater than 5 K owing to shock heating. In this case, the gas density must be low (approximately a few hundred particles per cm$^3$) so that thermalization does not occur. Using a large velocity gradient analysis, we find that such a low line ratio is consistent with a gas density $n_{\text{H}_2} < 1000$ cm$^{-3}$, although we cannot constrain the gas kinetic temperature. It is noted that the line ratio is expected to be closer to 1 in shock regions owing to the elevated gas kinetic temperature, which tends to populate the upper rotational levels. Better constraints of the physical parameters will have to await data of higher CO transitions.

Given the gas density and gas mass within the $21''$ beam, the filling factor of the molecular gas is of order $10^{-4}$. That is, the molecular gas must be in the form of small cloudlets. We can estimate whether these cloudlets are in pressure equilibrium with the surrounding environment. The ambient pressure surrounding the cloudlets comes from the magnetic pressure ($P_B$), cosmic-ray pressure ($P_{\text{CR}}$), and the gas pressure. The first two are equal in the case of energy equipartition and are both given by $B^2/8\pi$, where $B \approx 3 \mu$G is the equipartition magnetic field (Duric, Irwin, & Bloemen 1998). The gas pressure is the combined ionized ($P_{\text{ion}}$) and neutral ($P_{\text{nH}}$) gas pressure, each given by $P = nkT$, where $n$ is the gas number density, $k$ is the Boltzmann constant, and $T$ is the kinetic temperature of the gas. We assume the ionized gas is at $T = 10^4$ K and the electron density $n = 9 \times 10^{-4}$ cm$^{-3}$ at 4 kpc above midplane (from the electron density distribution given in Collins et al. 2000). For the H i gas, we use $T = 8000$ K and density $n_{\text{H}_i} = 2 \times 10^6$ cm$^{-3}$ at 4 kpc above midplane (from the vertical density distribution given in Irwin 1994).

From these values, we obtain $P_{\text{ion}} \sim P_{\text{CR}} \sim 4 \times 10^{-13}$, $P = 2 \times 10^{-15}$, and $P_{\text{nH}} = 2 \times 10^{-12}$ ergs cm$^{-3}$. The averaged internal pressure of the molecular gas is $P_{\text{int}} = 1 \times 10^{-12}$ ergs cm$^{-3}$, using parameters given in the previous paragraph. It seems that the magnetic and cosmic-ray pressure combined is sufficient to confine the clouds without internal gravitation.
4.2. Origin of Molecular Gas at High Latitude

Observations of molecular gas at high latitude are interesting in that they may explain high-latitude star formation. The key question is: How does the molecular gas reach such high latitude? Two possibilities may be considered. First, the molecular gas was formed in the disk and was ejected by the outflow that formed the H I supershell; and second, the molecular gas was formed at high latitude. Of course, a combination of these is also possible.

The gravitational potential energy ($E_{pE}$) of a cloud at a height, $z$, above the Galactic plane is calculated by solving the Poisson equation for a disk flattened in one dimension. We have assumed the Galactic value for the stellar scale height and the solar neighborhood value for the stellar mass density at midplane (325 pc and 0.175 $M_{\odot}$ pc$^{-2}$, respectively, from Freeman 1987) since the corresponding values for NGC 5775 are not known. Including both H I and H$_2$ gas, $E_{pE} = 2 \times 10^{56}$ ergs in F2. Note that $E_{pE}$ scales as the square of the stellar scale height so that if the scale height of NGC 5775 is twice that of the Milky Way, $E_{pE}$ will increase by a factor of 4. We estimate the total kinetic energy ($E_{K}$) of the gas (H I + H$_2$) to be $E_{KE} = 9 \times 10^{53}$ ergs. This includes the kinetic energy from the H I gas in F2, which is found to be $6 \times 10^{53}$ ergs using $M_{HI,F2}$ calculated above and assuming the expansion velocity is 62.5 km s$^{-1}$ (Lee et al. 2001), and the kinetic energy from the H$_2$ gas, which is found to be $4 \times 10^{53}$ ergs. The expansion velocity of the H$_2$ gas is taken to be half the averaged FWHM of all the CO line spectra (see § 3) in F2 minus, in quadrature, the expected line width from differential rotation within the beam (44 km s$^{-1}$) and the channel width (26 km s$^{-1}$), and is equal to 32.5 km s$^{-1}$. The predicted differential rotation within the beam is calculated using the H I rotation curve model given in Irwin (1994). Assuming that the supershell expands isotropically (a fair assumption based on the near circular morphology of F2), then the line-of-sight expansion velocity observed is a good estimate of the true expansion velocity of the supershell. Therefore, $E_{KE}$ of the supershell is more than 2 orders of magnitude lower than $E_{pE}$. The large difference in $E_{pE}$ and $E_{KE}$ suggests that the supershell is being observed at a time when it is about to fall back to the disk so that most of the energy is in the form of potential energy. We can therefore visualize an explosion at the midplane that created an expanding bubble of hot gas. In the process, neutral gas (atomic and molecular) is entrained in the ejecta, forming the supershell, reaching large $z$-height. Under the influence of the gravitational potential, the supershell is now about to plunge back, returning the gas to the star-forming disk. Such a recycling process has been proposed in the Galactic fountain model (Bregman 1980).

Another possibility for the molecular gas to exist at high latitude is that H$_2$ gas can be formed in situ via shock compression (e.g., Magnani 1987; Elmegreen 1988), occurring within H I preexisting in this region. The effect of a strong shock propagating through the interstellar medium is that dense molecular cloudlets can form owing to thermal instability in the shock regions (Koyama & Inutsuka 2000). The existence of H$_2$ emission (possibly due to shock ionization; see Lee et al. 2001) in F2 suggests that at least some of the molecular gas may be formed this way. It is more difficult to explain how the H I comes to reside at high latitude, in view of the large mechanical energy required (equal to $E_{pE}$). Various mechanisms have been examined in Lee et al. (2001), including supernova explosions and cloud impacts. In any case, this material would likely have originated within NGC 5775 since the mean radial velocity agrees with the orbital velocity of the disk. Finally, assuming a typical Galactic dust-to-gas ratio, the high-latitude molecular clouds could be emitting substantial infrared radiation and have indeed been observed at 850 µm (R. S. Brar et al. 2002, private communication).

5. CONCLUSIONS

This Letter reports the detection of high-latitude molecular gas in NGC 5775. The shell-like distribution of the CO emission coincides exactly with that of the H I supershell, suggesting that we have detected the molecular shell associated with the H I supershell. The existence of the molecular shell means that molecules are not destroyed during the ejection of the supershell and are entrained in the expanding flow to reach high latitude. Some of the molecular gas may have been formed in situ, via shock compression of preexisting H I gas. The CO $J = 2-1/1-0$ line ratio (0.34 ± 40%) suggests that the gas density in the supershell is low and the gas is subthermally excited. The molecular gas is probably in the form of cloudlets that are confined by magnetic and cosmic-ray pressure. Based on energetics grounds, we propose that the supershell may be at a stage where it is about to plunge toward the disk of the galaxy, returning the gas to the bulk of the gas reservoir of the galaxy.

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