SMA Observations of Haro 2: Molecular Gas around a Hot Superbubble

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ABSTRACT

Haro 2, a nearby dwarf starburst dwarf galaxy with strong Ly α emission, hosts a starburst that has created outflows and filaments. The clear evidence for galactic outflow makes it an ideal candidate for studying the effects of feedback on molecular gas in a dwarf galaxy. We observed CO(2-1) in Haro 2 at the Submillimeter Array in the compact and extended configurations, and have mapped the molecular emission with velocity resolution 4.1 km s$^{-1}$ and spatial resolution 2.0 $\times$ 1.6$''$. With this significant increase of resolution over previous measurements we see that the molecular gas comprises two components: bright clumps associated with the embedded star clusters of the starburst, and fainter extended emission east of the starburst region. The extended emission coincides with an X-ray bubble and has the kinematic signatures of a shell or bubble expanding with velocity $\pm$35 km s$^{-1}$. We suggest that the starburst winds that created the X-Ray bubble have entrained molecular gas, and that the apparent velocity gradient across the photometric axis is an artifact caused by the outflow. The molecular and X-ray activity is on the east of the galaxy and the ionized outflow and optical filaments are west; their relationship is not clear.

Keywords: galaxies:individual (Haro2), galaxies: kinematics and dynamics, galaxies: starburst

1. INTRODUCTION

Blue compact dwarf (BCD) galaxies form stars in environments quite different from gas-rich spirals or luminous infrared galaxies. Often rich in atomic gas, BCDs are typically underluminous in CO and presumably molecular gas-poor; the origin of the molecular gas from which the stars are forming is unclear. Perhaps star-forming molecular clouds form from their reservoirs of atomic gas; alternatively, molecular gas could be acquired from other galaxies via accretion or merger. Another urgent question is how starburst feedback operates on molecular gas. The gravitational wells of dwarf galaxies are not as deep as spirals’ and it is easier for them to lose gas to winds. However, molecular gas has greater cooling capacity than atomic, which can cause galactic winds to fail and inhibit gas dispersal. This can have ramifications for the escape of ionizing radiation from the starburst. Haro 2 (Mrk 33, Arp 233, UGC 5720) is one of the best local targets in which to study the processes of star formation fueling and feedback in a dwarf galaxy. One of the most luminous BCDs, Haro 2 has a very blue nucleus (Haro 1956) of moderate metallicity ($Z \sim Z_\odot/3$), with strong ultraviolet and optical emission lines and WR features (Kunth & Joubert 1985; Loose & Thuan 1986; Kinney et al. 1993), and bright radio continuum emission (Beck et al. 2000; Aversa et al. 2011), indicating very recent (< 10 Myr) star formation. Haro 2 is one of the closest Lyman α emitting galaxies. Its strong, redshifted Ly α line is probably due to a outflow of ionized gas at $\approx$ 200 km s$^{-1}$ with respect to the galaxy (Lequeux et al. 1995; Meier et al. 2001). The ionized outflow is presumably driven by the massive stars in the starburst. Summers et al. (2001) observed the soft X–ray emission of Haro 2 with HRI on ROSAT with 1.5$''$ pixels and saw “an extended, complex shell-like morphology”; found hard emission concentrated in three point sources as well as the widely distributed soft emission.

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CO(1–0), CO(2–1), and CO(3–2) lines have been detected with single dishes (Arnault et al. 1988; Sage et al. 1992; Barone et al. 2000; Meier et al. 2001; Mao et al. 2010; Israel et al. 1995). Haro 2 is comparatively weak in low J lines of CO, as is common in BCDs.

With sensitive array observations, CO can be mapped at the scales of individual giant molecular clouds (GMCs) in nearby galaxies, allowing the star formation process to be studied at the cluster scale. The first interferometric maps of CO and HI in Haro 2 were by Bravo-Alfaro et al. (2004); their map of CO(1–0) revealed unusual halo-like emission around the galaxy and suggested that the photometric and kinematic axes are misaligned. This motivated us to observe Haro 2 in a higher transition; CO lines from high J are often stronger than CO(1-0) in BCDs, especially in regions of star formation (Israel et al. 1995; Meier et al. 2001). We accordingly observed Haro 2 in the CO(2-1) line with the Submillimeter Array (SMA) on Mauna Kea in both the extended and compact configurations, giving spatial resolution better than $2''$ and velocity resolution of $\approx 4$ km s$^{-1}$ over the star forming region (observational parameters are in Table 1). We combine this data cube with archival radio continuum and optical images for a full picture of molecular gas kinematics in the center of Haro 2 which is very different from the earlier results.

2. OBSERVATIONS

We observed the CO(2-1) line in both the extended and compact configurations of the Submillimeter Array (SMA). The compact configuration, which has a maximum baseline of 70 m, was used on 13/6/15 and the extended configuration with maximum baseline 220 m on 19/4/2016. Callisto was the absolute flux calibrator. Full parameters of the observations and the range of spatial resolutions achieved are in Table 1. The data was calibrated in MIRIAD and imaged with AIPS and CASA 4.7.0. Combining the extended and the compact configuration data created a data cube with spatial beam of $1.96 \times 1.61''$, almost as high as the extended configuration, but with the sensitivity of the compact configuration to see large-scale structures; the largest structure that can be mapped is $\sim 210''$, corresponding to 22 kpc at the galaxy’s distance of 21 Mpc. Final noise levels in the individual combined channel maps are 17 mJy beam$^{-1}$. The integrated intensity (moment 0) image was constructed from all channels stronger than $> 1.5\sigma$. The intensity weighted mean velocity and dispersion maps (first and second moments) were constructed from emission $> 4\sigma$. Barone et al. (2000) obtained $I_{CO} = 6.4 \pm 1.3$ K km s$^{-1}$ for Haro 2 at the IRAM 30-m telescope for a flux density $\approx 0.7$ Jy. We estimate that about 60% of the single dish CO(2–1) emission is represented in the SMA images; as this is roughly consistent with the 15% uncertainties in absolute flux calibrations of both observations, it does not necessarily indicate that an extended component of emission has been resolved out.

3. SMA OBSERVATIONS OF CO(2–1): DISTRIBUTION OF EMISSION WITHIN HARO 2

3.1. Basic Structure: Starburst Clumps and an Extended Northeast Wing

The CO(2-1) total integrated intensity map of Haro 2 is displayed in Figure 1, as contours on the H$\alpha$ image from HST. The total extent of the CO emission is about 1.5–2 kpc, about the size of the optical image. The brightest CO emission comprises two strong compact sources in the starburst region. Figure 1 shows that that the extended CO emission lies mostly east and north of the starburst, and that the edges of the extended CO lie near weak dust lanes, indicating that the extended CO is on the near side of the galaxy. These features are also seen in the CO(1-0) images of Bravo-Alfaro et al. (2004).

The starburst in Haro 2 has been mapped in the radio continuum by Beck et al. (2000) and Aversa et al. (2011) and found to comprise two bright clumps of thermal emission. Because of their size, mostly thermal radio spectrum, strong [NeII] 12.8 $\mu$m line (in the Spitzer Heritage Archive), location in a region of enhanced star formation, and appearance in 3.6 $\mu$m and 4.5 $\mu$m images (from IRAC on Spitzer) these radio continuum sources are most likely groups of heavily obscured young star clusters. Figure 2 shows the CO(2-1) integrated intensity alone and overlaid with a high resolution map of the thermal radio continuum and demonstrates that the strong compact CO sources generally coincide with the two bright starburst clumps; the eastern continuum source is nearly coincident, and the western source is slightly offset. We do not see CO(2-1) west of the starburst nucleus, although there are H$\alpha$ filaments.

$S(CO(2 – 1))$, the total flux including the red and blue extremes of emission, is 110 Jy km s$^{-1}$. The CO(1-0) flux can predicted from this result and correction factors of 0.8 (from $T_b$, the Rayleigh-Jeans correction for cool gas) and 1/4 (for $\nu^2$) to be $0.2 \times S(CO(2 – 1))$ or $22 Jy$ km s$^{-1}$, in good agreement with Bravo-Alfaro et al. (2004)’s result of 24.3 Jy km s$^{-1}$. With Bravo-Alfaro et al. (2004)’s $\chi_{CO}$ this gives a total molecular mass of $1.5 \times 10^8 M_\odot$.

Figure 3 compares the (1-0) and (2-1) maps and shows the (2-1) extending east of the (1-0) emission. A similar result came from a single-dish measurement of CO(3-2) in the JCMT Nearby Galaxies Legacy Survey (Wilson et al. 2012).
The galaxy was observed in jiggle-map mode with 14.5″ resolution, and their figure C26 shows the (3-2) emission clearly extended north and east of the optical nucleus, coincident with the (2-1) appearance. That the higher CO transitions are consistently stronger than the (1-0) east of the galaxy implies that the eastern gas is warm and the upper levels populated, as is seen near other strong starbursts (Consiglio et al. 2016). This will be discussed further in relation to the X-ray emission below.

Bravo-Alfaro et al. (2004) report ‘possible’ CO(1-0) concentrations south and NW of the main emission region in a map made with a 3.3 × 2.6″ beam. We do not see these features in the full resolution maps. By tapering the beam to ≈ 3″ we find emission at the 2–4σ per beam level in those positions. We believe these clouds are real, especially the extended NW feature which covers several beams, but the signal-to-noise at this time is too low for meaningful study and they will not be discussed further here.

4. SMA OBSERVATIONS: THE KINEMATICS OF THE MOLECULAR GAS

The kinematics of gas in Haro 2 are of particular interest because it is one of the closest Lyman α emitting galaxies. Since Haro 2 does not have a particularly low metallicity, it has been suggested (Lequeux et al. 1995) that the escape of Lyman continuum photons is due to gas kinematics, and indeed there is a suggestion of outflow in the ionized gas (Legrand et al. 1997). How this might compare to the kinematics of the molecular gas is an important question. Figure 4 displays samples of channel maps of CO(2–1) emission (a complete set of channel maps is in the Appendix). The CO(2-1) emission in Haro 2 spans a total velocity range of ≈ 250 km s\(^{-1}\) FWZI, from about 1350 to 1600 km s\(^{-1}\), with a centroid of 1470 km s\(^{-1}\). Bravo-Alfaro et al. (2004) found 1440 km s\(^{-1}\) as the center of the HI line. The kinematic axis of the HI gas and the photometric axis of the galaxy appear to be misaligned; the HI has almost no velocity gradient along the major axis but a strong gradient at right angles to it, as is also the case for Hα (Petrosian et al. 2002). Bravo-Alfaro et al. (2006) found that the molecular gas distribution coincides with the major axis of the galaxy seen in blue light and had a complex velocity profile ‘not consistent with simple rotation’. The
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Figure 2. Top: the integrated intensity (moment 0) of CO(2-1). The color wedge units are Jy/km (m/s) and the contour levels are multiples of 800; base contour is 1110. Bottom: the 6 cm radio continuum, showing the clumps of young star clusters in the starburst region, overlaid with contours of CO(2-1) integrated emission as in the top figure.

emission in their CO data cube only covered velocities of 1378 to 1503 km s$^{-1}$. It is probable that the CO(1–0) emission in their cube was undetected in the high velocity channels due to low signal to noise, which can explain some of the differences with the current results.

Figure 5 displays the first moment (intensity-weighted peak velocity) and second moment (FWHM) of the CO(2-1) line, with the radio continuum contours superimposed. They show a velocity gradient along the axis connecting the starburst clumps, and also extended blue emission with a complex velocity field north and east of the starburst. We first discuss the kinematics of the central starburst region, which is the location of the majority of the CO emission.

4.1. Molecular Gas Kinematics in the Starburst

The channel maps of Figure 3 clearly show two velocity components associated with the starburst: one at $\sim$ 1510 km s$^{-1}$ on the southeast star-forming clump and another component at $\sim$ 1470 km s$^{-1}$ on the north clump, giving a centroid of 1490 km s$^{-1}$. 
How do these velocities compare to those seen at optical wavelengths? The $H\alpha$ spectra of Meier et al. (2001) found velocities of $\approx 1430$, $\approx 1450$ and $\approx 1465$ on their $H\alpha$ knots 1, 2, 3 respectively. This argues that their $H\alpha$ knots 1 and 2 are not associated with the star forming clumps seen in the radio, or that the $H\alpha$ is arising from a champagne flow on the near side. $H\alpha$ knots 1 and 2 are north of, and stronger in $H\alpha$, than is knot 3. Their knot 3 corresponds to the the northern radio source. That the southern radio source has no associated $H\alpha$ is a sign of high local extinction, which plays an important role in the appearance of this galaxy’s core. The top row in Figure 6 shows the velocity as a function of position along the main body of the galaxy as defined by the radio clumps. The velocity shift between the two sources is consistent with the gradient set by the $H\alpha$ clumps, further north on the same line.

4.2. Molecular Gas Northeast of the Starburst: an Expanding CO Bubble

In addition to the molecular gas associated with the star formation, there is an extended ($\sim 1.5$-2 kpc) complex of emission over the 1360-1470 km s$^{-1}$ range to the north and east of the galaxy. The first and second moment maps of Figure 5 and the channel maps in Figure 4 and the Appendix show that the extended eastern emission is entirely blue of the main starburst; the blue velocities of the extended eastern emission have no counterpart in the optical spectra. The eastern emission is concentrated at two velocities $\approx 45$ km s$^{-1}$ apart; these appear in the channel maps of Figure 4 as two 'horns' extending east from the starburst region. These features appear clearly in position-velocity diagram in the second row of Figure 6. The gas in the PVD forms the ‘ring’ typical of an expanding shell or bubble (‘expanding’ because we believe the CO to be on the near side of the galaxy) with some breaks because of the clumpy
The spatial structure of the gas, and the line profile through the eastern region, shown in Figure 7, agrees with the PVD in having two velocity peaks separated by roughly $60\,\text{km\,s}^{-1}$.

To summarize: the channel maps, PVD and line profiles of the molecular gas east of the starburst all demonstrate the kinematic signatures of an expanding bubble or outflow cone, with expansion velocity $\sim 35 - 40\,\text{km\,s}^{-1}$.

### 4.2.1. The Molecular Bubble and the X-Ray Emission

The large-scale activity reflected in the molecular outflow appears as well in the high energy regime. Summers et al. (2001) observed Haro 2 with HRI on ROSAT with a $\sim 5''$ beam and 1.5'' pixels and saw "an extended, complex shell-like morphology". Oti-Floranes et al. (2012) observed with CHANDRA over a wider energy range and with 0.49'' pixels. Their image of the soft (0.2-1.5 KeV) emission is very similar to the ROSAT result; they find in addition 3 point-like sources of hard (2.5-8.0 KeV) x-rays. How does the structure correspond to the molecular gas? In Figure 8 we overlay the CO(2-1) map on the full resolution ROSAT X-ray image. The CO(2-1) line agrees well with the soft X-ray distribution: an X-ray shell coincides with the CO bubble and the base of the shell with the starburst clusters. Oti-Floranes et al. (2012)'s dominant hard x-ray source, X1, agrees with the brightest near-infrared clump in NICMOS images. We identify the near-infrared peak with the brighter (northern) sub-clump in the southern starburst...
Figure 5. Intensity-weighted mean velocity (left) and velocity dispersion (right) of CO(2–1) in Haro 2. The units of the color wedges are $\text{km s}^{-1}$. The radio contours of Figure 2 are superimposed on the moment maps.

region of Figure 2, although the formal coordinates disagree by about 1''; Oti-Floranes et al. (2012) also note this inconsistency in the coordinates. With this alignment, the secondary hard X-ray source X2 agrees with the weaker southern sub-clump. We do not have a candidate for the X3 source that Oti-Floranes et al. (2012) suggest may not belong to the galaxy.

The CO(2-1) agrees spatially with the X-ray better than does the CO(1-0); Bravo-Alfaro et al. (2004) show in their Figure 8 that the X-ray extends further to the east than does the CO(1-0) emission. That the CO(2-1) is a better match than the (1-0) with the X-ray may be partly due to the improved resolution but is primarily, we believe, because the gas is warm or hot, as was discussed above in Section III. We conclude that the molecular bubble or shell is associated with the hot X-ray emitting gas. The CO line profile here resembles that on an X-ray source in He2-10, (Beck et al. 2018) and CO lines are seen emitted from the edges of other bubbles and superbubbles (e.g. Matsushita et al. 2005, Sano et al. 2017, Tsai et al. 2009). The molecular gas is probably concentrated in the thin, dense shell created in the 'snowplow' stage of bubble expansion (Summers et al. 2001).

4.2.2. Kinematics of the X-Ray Bubble, Molecular Gas and $H\alpha$

Summers et al. (2001) model their X-ray bubble as resulting from the stellar winds of the nuclear starburst under the assumption that it is the same process as the ionized outflow observed in $H\alpha$. They accordingly use the size and expansion velocity Legrand et al. (1997) found for the $H\alpha$ system to determine parameters of the the X-ray bubble. But the current data show clearly that the X-ray and molecular bubble is east of the nucleus. Although the spectra of Legrand et al. (1997) cannot be registered spatially because of the very poor seeing, it is reasonable to associate the ionized outflow they observe in $H\alpha$ with the $H\alpha$ filaments seen in deep images west of the nucleus. The velocities are another discrepancy between the ionized and molecular kinematics: the ionized outflow has expansion velocity $\sim 200$ km s$^{-1}$, significantly higher than the $\sim 35$ km s$^{-1}$ of the molecular shell.

We conclude that the nuclear region of Haro 2 drives two outflows: to the west, a fast ionized outflow which has created $H\alpha$ filaments, and to the east a bubble of hot, X-ray emitting gas which has entrained warm molecular gas.

How will the results calculated by Summers et al. (2001) change in this model? The important difference is the relatively slow expansion velocity; $\sim 35$ km s$^{-1}$ instead of $200$ km s$^{-1}$ for $v_b$ in their Equation 8 gives an age estimate of $1.8 \times 10^7$ yr, instead of $3.2 \times 10^6$ yr. The longer time is more consistent than the short with other estimates of the age of the relatively mature starburst of Haro 2. The longer lifetime in turn reduces the mechanical injection energy derived; Summers et al. (2001)’s Equation 1 gives $1.35 \times 10^{39}$ erg s$^{-1}$ instead of $2.4 \times 10^{41}$ erg s$^{-1}$. Such energy can be readily supplied by the stellar population of any one of the nuclear clumps. The most likely driver is in the northern source, as its velocity overlaps with velocities in the CO bubble.
Figure 6. Position-Velocity diagrams of the CO(2-1) emission through the starforming clusters (top row) and the extended east emission (bottom row). In each row the left image shows the line defining the PVD in the right image, overlaid on a map in a single velocity channel. Negative offsets are east.

4.2.3. Re-evaluating the Global Kinematics of Haro 2

Identifying the blue-shifted molecular gas NE of the galaxy as a CO bubble means that we must re-appraise the overall CO and HI kinematics described by Bravo-Alfaro et al. (2004). While the CO bubble holds only a small fraction of the total gas mass, it is so spatially distinct that it appears clearly in first moment maps and create an apparent velocity gradient NE to SW, at right angles to the optical major axis. We believe this is what Bravo-Alfaro et al.
5. SUMMARY AND DISCUSSION

We report observations of CO (2-1) in Haro 2 which combine the SMA in extended and compact arrays to give beam sizes $\approx 2 - 7''$. The major findings are:

- Approximately half the molecular gas is in two clumps, kinematically and spatially distinct and coincident with the bright radio sources which are identified as obscured starburst clumps.
• Approximately half the molecular gas is in a bubble or shell north-east of the galactic nucleus, with expansion velocity $\sim 35 - 40 \text{ km s}^{-1}$.

• The CO bubble coincides with an X-ray superbubble which is believed to have been created by stellar winds in the starburst, and with no other known sources. It is probably gas entrained by the hot gas in the X-ray emitting bubble.

• The bubble or shell of molecular gas, probably entrained by the hot gas in the X-ray emitting superbubble, may be unusually warm; it should be observed with high spatial resolution in other CO transitions.

• The well-known misalignment of the optical and kinetic axis in Haro 2 now appears to be an artifact caused by low spatial resolution of earlier observations.

It is not clear how the stellar activity that created the molecular bubble is related to the ionized outflow and $H\alpha$ filaments seen west of the galaxy. Is one starburst clump driving two outflows of different types in different directions? Are the ionized and molecular outflows driven by two different sources? Is there an ionized outflow connected to the molecules and X-rays that has not yet been detected? It would be very useful to observe Haro 2 further in optical emission lines to determine the full extent of its outflow activity, and in higher transitions of CO to determine conditions in the molecular clouds associated with the X-ray superbubble.

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**Facilities:** SMA

**Software:** CASA, AIPS, ds9

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Table 1. Observational Parameters

| Date      | Telescope       | Wavelength | Beam Size       | Spectral Channels | noise $Jy/bm$ |
|-----------|-----------------|------------|-----------------|-------------------|--------------|
| 18/4/16   | SMA-Extended    | 230 Ghz    | $1.25 \times 0.97''$ | 65 $\times$ 4.2 km s$^{-1}$ | $9 \times 10^{-3}$ |
| 04/01/16  | SMA-Compact     | "          | $7.11 \times 4.55''$ | "                 | $1.9 \times 10^{-2}$ |
| n.a.      | SMA-Combined    | "          | $1.96 \times 1.61''$ | "                 | $1.7 \times 10^{-2}$ |
| 02/11/90  | VLA-C array     | 4.86 Ghz   | $0.59 \times 0.47''$ | n.a.              | $8.0 \times 10^{-5}$ |
Figure 9. Velocity channel maps of Haro 2 showing all velocity channels, overlaid on the moment 0 total emission map. The contours are $4 \times 10^{-2} \times 2^{n/2}$ Jy/bm and the greyscale range is -0.25 to 12.37 (Jy/bm)(km s$^{-1}$).