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H I and CO Emission in Blue Compact Dwarfs: Haro 2 and Haro 4/26

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Abstract. We present VLA H I imaging of two actively star-forming dwarf galaxies, Haro 2 and Haro 4, and of the spiral galaxy NGC 3510 (Haro 26), some 22′ SW of Haro 4 (8.5 kpc). We also present a map of the CO(1–0) distribution of Haro 2 obtained with the OVRO millimeter interferometer and give an upper limit for CO(2–1) from Haro 4. Our results, based on the distribution of the atomic and molecular gas, suggest that both dwarfs are in distinctly different stages of galaxy interaction. The striking kinematics of Haro 2 indicate a recent merger event, whereas the H I distribution and kinematics of Haro 4 and the neighboring spiral NGC 3510 suggest that they are involved in a tidal interaction.

1. Introduction

Blue compact dwarf galaxies (BCD) show high gas content and low metallicity suggesting that since they were formed they can only have undergone a few bursts of star formation. In this work we study the neutral atomic (H I) and molecular (CO) components in two star–forming dwarf galaxies, searching for the physical mechanisms which trigger star formation. Two kind of triggers may be at work, i.e., internal, dynamical instabilities or an external mechanism, especially tidal interactions (Taylor et al. 1994, Pustilnik et al. 2001). Mapping both the atomic and molecular components is key to addressing the question of what might trigger star formation in BCDs. To date, very few of these objects have been mapped in H I (van Zee et al. 2001) and even fewer with millimeter interferometers (Walter et al. 2001). In order to increase the sample of galaxies studied in reasonable detail, we have observed the H I and CO of

Haro 2 and Haro 4; the latter is suspected to be interacting with the spiral galaxy NGC 3510, at a projected distance of 8.5 kpc to the SW of Haro 4 (we assume H_o=75 km s^{-1} Mpc^{-1}).

2. Observations

We mapped the H I in Haro 2 and the presumably interacting system Haro 4–NGC 3510 with the VLA[1] in C and D configurations. Haro 2 was also observed in the CO(1–0) transition with the Owens Valley Radio Observatory (OVRO) millimeter array. We also obtained single-dish CO(2–1) observations of Haro 4 at the Caltech Submillimeter Observatory (CSO); however the galaxy was not detected at an rms level of 14 mK (see the discussion below). Table 1 gives a summary of our H I observations. For more details see Bravo–Alfaro et al. (2002).

Table 1. VLA H I Parameters of Combined C+D Data

(1) Field	(2) Time hrs	(3) Beam size	(4) Resol kpc	(5) Vel.Resol km s^{-1}	(6) rms mJy/beam
Haro 2	3.6	14.8 × 14.1	1.4	5	0.37
Haro 4/26	3.9	15.5 × 14.0	0.6	5	0.39

3. Results

Haro 2 is H I rich and is clearly detected in this VLA survey. Figure 1 (left) shows a full resolution (~15″) map of the H I surface brightness superposed on an optical DSS image. The orientation of the H I coincides with that of the optical isophotes, and the H I extends beyond the optical disk (D_{25} ~1′). We find a ratio D_{HI}/D_{opt} ~ 1.3 and an H I mass of 1.8 ×10^8 $M_\odot$. Figure 1 (right) shows the H I velocity field; this map is surprising as it reveals that the kinematic major axis is nearly perpendicular to the major axes of the optical light and the H I distribution. A cursory inspection of the H I channel maps confirms this behavior (Bravo–Alfaro et al. 2002). A scenario which explains the kinematics, the H I content, and optical morphological type of Haro 2, is a recent merger with an H I cloud (from optical surface photometry this galaxy is classified as an elliptical by Loose & Thuan, 1986).

Figure 2 (left) shows in grey scale the zeroth velocity moment of the CO(1–0) line in Haro 2, superposed with the contours of the H I map. We detect a clear arclike feature extending from southeast to northwest, and containing

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

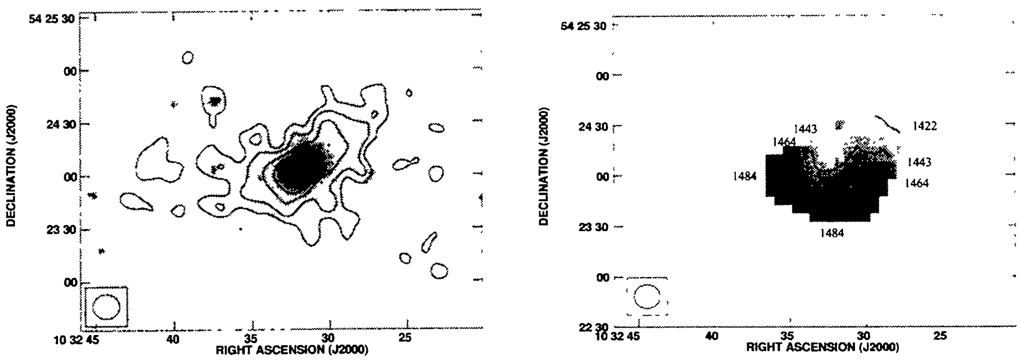

Figure 1. (Left) H I map of Haro 2 superposed on a DSS B–band grey-scale image. Contours are 2.0 (5 σ), 4.0, 8.1, 12.2 and 16.2$\times 10^{20}$ cm^{-2}. (Right) The velocity field for Haro 2; numbers indicate heliocentric velocity in km s^{-1}. The FWHM beam is indicated in the lower left and measures 14.7″ × 14.0″.

find $F_{CO} \sim 18$ Jy km s^{-1}. Assuming a Galactic CO–to–H_2 conversion factor of $X = N_{H_2}/I_{CO} = 3 \times 10^{20}\,\mathrm{cm}^{-2}\,(\mathrm{K\,km\,s}^{-1})^{-1}$ with an extra factor of 1.36 to account for helium, we estimate $M_{gas} \sim 10^8\,M_\odot$ and $9 \times 10^7\,M_\odot$ for the full galaxy and its central regions, respectively. From these values we estimate a ratio $M_{H\,I}/M_{H_2} \sim 1.5$.

Haro 4/Haro 26 are suspected to be involved in a tidal interaction as suggested by Figure 2 (right), where we show the integrated H I maps superposed on an optical DSS image. This figure shows the highly compact nature of the H I distribution of Haro 4 (with only a slight hint of rotation). In contrast, NGC 3510 is well resolved by our beam and spans a much larger range in ve-

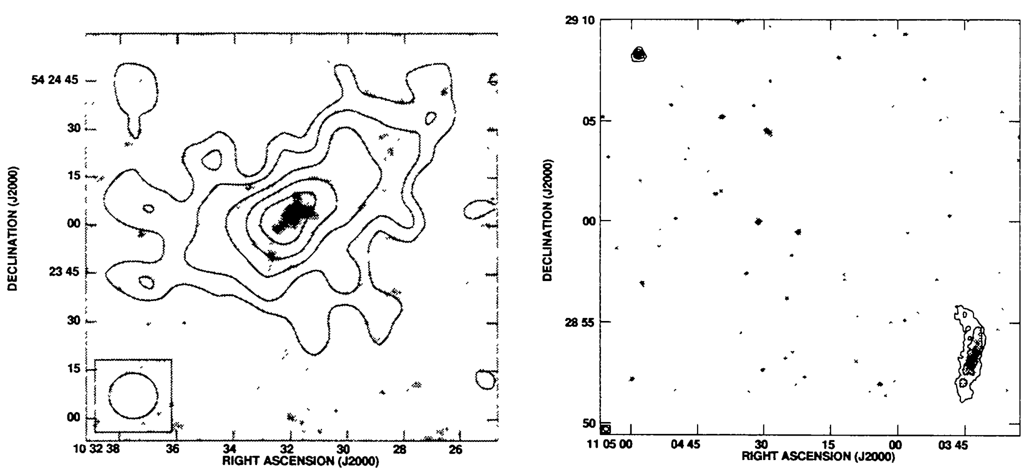

Figure 2. (Left) Zeroth moment map of the CO(1–0) emission of Haro 2 shown in grey scale. The contours outline the H I as in Fig. 1. (Right) H I column density distribution of Haro 4 (top–left) and Haro 26 (NGC 3510, in the bottom–right) superposed on a DSS B–band grey-scale image. Contours are 2.1 (5 σ), 6.2, 12.3, and 18.5$\times 10^{20}$ cm^{-2}. The FWHM is indicated with a circle in the lower–left corner, 15.5″ × 14.0″.

H I distribution of Haro 4 (with only a slight hint of rotation). In contrast, NGC 3510 is well resolved by our beam and spans a much larger range in velocity. The midplane shows severe warping in the north that might be due to a recent interaction with Haro 4. This warp is confirmed by the velocity field (see Bravo–Alfaro et al. 2002) which shows that the northern tip clearly tends towards Haro 4's position in the NE. We did not detect Haro 4 in CO(2–1). Based on the rms of 14 mK (T_{mb}) and assuming a line width of $\sim$ 35 $\mathrm{km\,s^{-1}}$, we derive for Haro 4 an upper limit of $\sim$ 0.5 $\mathrm{K\,km\,s^{-1}}$, compared to a total single–dish flux of Haro 2 of 6.5 $\mathrm{K\,km\,s^{-1}}$ (Sage et al. 1992).

In each BCD, we measured the H I column density and compared it to the empirical threshold for star formation, i.e. the minimum gas column density necessary for star formation to occur. This is commonly believed to be around 10^{21} atom $\mathrm{cm^{-2}}$ (Toomre 1964). We find that the neutral gas distributions of both galaxies show regions of high H I column density ($> 2\times10^{21}$ atom $\mathrm{cm^{-2}}$) near the center of the optical counterparts. In the case of Haro 2, the CO emission lies within the highest H I contour, where the column density is higher than 10^{21} atom $\mathrm{cm^{-2}}$, confirming this empirical threshold for star formation.

We conclude that some galaxies usually considered to be isolated systems might very well be in different stages of interaction: either after a recent merger with a low–mass cloud, as seems to be the case for Haro 2, or in the middle of a relatively long–distance tidal interaction, as shown in the case of Haro 4/Haro 26.

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