Tracing the Molecular Gas in Star-forming Dwarf Galaxies – The Case of the BCDG Haro 2

T. Fritz[1], S. Hüttemeister[2], N. Neininger[1], U. Klein[1]

[1]Radioastronomisches Institut Univ. Bonn, Auf dem Hügel 71, D-53121 Bonn, Germany
[2]Astronomisches Institut der Ruhr-Universität, Postfach 102148, D-44780 Bochum, Germany

1 Introduction

The study of the molecular gas in dwarf galaxies allows to probe the interplay of ISM and star-formation over a wide range of metallicities and thus gives clues to the understanding of the early phases of galaxy evolution. Since molecular hydrogen itself is barely detectable, we have to rely on other tracers of the dense ISM. Unfortunately, the CO emission commonly used to study the molecular component of the ISM becomes unreliable in the hostile low-metallicity environment of star forming dwarfs. Shielding becomes less effective with decreasing metallicity, allowing the pervasive radiation field to photo-dissociate the CO and ionize C while H_2 remains less affected (see e.g. Bolatto et al. (1999) for a details). The ^{12}CO line emitting surfaces of the dense molecular cloud cores shrink, enclosed by a layer of atomic carbon and an envelope of C^+ with increasing relative thickness. In very metal-poor dwarf galaxies, the molecular gas directly associated with the PDRs at the sites of star-formation becomes hence undetectable in CO. In these cases, C^+ which shares a common volume with the molecular hydrogen might be a good tracer for the dense ISM as indicated by the strong C II lines from dwarf galaxies (Madden et al. 1997).

The arguments stated above suggest a steep metallicity dependence of the $X_{\rm CO}$ conversion factor of integrated CO line intensity to H_2 column density as actually found for a small sample of galaxies by Arimoto et al. (1996) and Wilson (1995). But the strong radiation field is not only responsible for the photo-dissociation of CO, it also heats the gas and thus increases the CO excitation temperature and line intensity. As Wolfire et al. (1995) and Bolatto et al. (1999) point out the observable CO line intensity is the result of a complex interplay of abundance effects, the structure, size and temperature of the CO line emitting cloud layers and the energy balance of the gas. The $X_{\rm CO}$ conversion factor is hence a local property, strongly depending on the excitation conditions in the CO line emitting region – thus also giving insights in the (expected) C I and C II line emission as the major coolants of the ISM. The study of $X_{\rm CO}$ is the only key to the understanding of star-formation in metal-poor environments until detailed C I and C II observations of dwarf galaxies become available. The measurement of local $X_{\rm CO}$ values in extragalactic systems is mainly based on three methods: (1:) Comparison of virial masses with masses derived from CO luminosity. This approach needs high-resolution CO data and is not applicable to extreme environments where the clouds are far from virialization. (2:) Determination of H_2 densities by the means of radiative transfer analysis. Observations of higher CO transitions and isotopomeres are needed to find unique solutions. (3:) From the difference of the distribution of neutral hydrogen and the dust, assuming a gas–to–dust ratio that does not show local variations. The lack of high-resolution IR data restricts the use of this method to nearby systems. Due to the intrinsicly weak CO lines of dwarf galaxies, the studies of $X_{\rm CO}$ are very scarce so far. While most star-forming dwarf galaxies remained elusive

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to CO searches in the past (e.g. Barone et al. 2000), Haro 2 is one of the very few objects where high-resolution and multi-transition CO studies are feasible.

2 The BCDG Haro 2 – a case study

Haro 2 is a prototypical blue compact dwarf galaxy (BCDG) at 20.5 Mpc distance with an optical extent of $68'' \times 44''$ and an absolute blue magnitude of -18.4^m (Loose & Thuan 1986) – brightened by the newly formed stars. The star-formation in this metal-poor (1/3 solar) galaxy, as traced by Hα emission, is confined to the central region. We observed this 'nucleated elliptical' BCDG in CO(1→0), CO(2→1), CO(3→2), ^{13}CO(1→0) and ^{13}CO(2→1) using the IRAM 30m, the PdBI and the HHT / SMTO 10m (see Fritz (2000) for details).

2.1 Molecular cloud complexes

The CO emission found in the single-dish and in the interferometric maps is surprisingly extended. While about half of the CO line emission is closely associated with the central star-forming region, we also detect large molecular cloud complexes and a more diffuse distributed gas component in the outer, quiescent regions of Haro 2. The PdBI cubes reveal a very complex velocity structure of the molecular gas with high dispersion in the central region and kinematically decoupled outer lobes, which show no clear sign for an overall rotation.

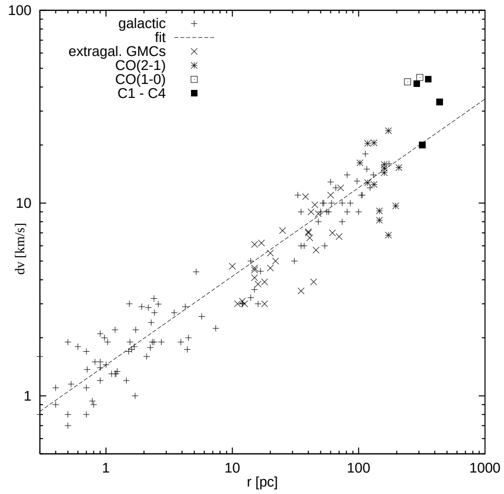

Figure 1: Size–linewidth relation (Larson law) of the molecular cloud complexes in Haro 2 (CO(1→0): unresolved [squares]; CO(2→1) complexes [*]) in comparison to Galactic clouds & GMCs [+] (see Heithausen (1996) and references therein) and to GMCs in local group galaxies [x] (see Taylor et al. (1999) and references therein). The line fits the Galactic molecular clouds (Heithausen 1996).

The substructure visible in the higher resolved CO(2→1) cube can be decomposed into distinct features. The linear resolution is not sufficient to resolve individual GMCs but the fact that the cloud complexes do not deviate significantly from the empirical galactic size–linewidth relation (Fig. 1) indicates that they are indeed physical entities. One can not conclude from the size–linewidth correlation that the cloud complexes are virialized. The observed relation might also result from completely different interrelation of cloud mass and size (e.g. fractal cloud fragmentation; see Heithausen (1996) for an example of unvirialized clouds which follow the Larson law). However, the 'normal' mean CO(2→1)/CO(1→0) line ratios of 0.7 derived for the individual cloud complexes and the large distance between the studied complexes and the nucleus of Haro 2 lead us to the conclusion that these objects are undisturbed and that the assumption of virialization is valid. Virial mass estimates for the *unresolved* cloud complexes are clearly overestimating the true mass. The comparison with the masses derived from the CO-luminosity yield hence *upper limits* of $X_{\rm CO}$. We find a mean $X_{\rm CO} \leq 1.2 \pm 0.6$ times the galactic standard value of $X_{\rm gal} = 2.3 \cdot 10^{20}$ cm^{-2} (K km/s)$^{-1}$ (Strong et al. 1988). This is lower than expected from the $X_{\rm CO}$–metallicity relation.

2.2 The physical state of the dense ISM

We use the most simple of the non LTE radiative transfer approaches – the large velocity gradient (LVG) approximation – to analyze the observed CO line ratios (see Weiß et al. (2000) for details on the used algorithms). The available CO(3→2) and ^{13}CO data limit this study to a resolution of 22″. Hence only the physical properties of *average* molecular clouds (or, more precisely: average CO line emitting volumes of the ISM) within one beam are probed. Nevertheless, the velocity components can partly be identified with the different emission regions seen in the high-resolution data cubes. Fig. 2 shows the results of the LVG analysis of such a velocity component of a central pointing, representing the more quiescent clouds in the central region. It also demonstrates how valuable ^{13}CO observations are to pin down the physical conditions of the molecular gas. The fact that LVG solutions for this pointing and velocity component exist at all also indicates that the CO emission is predominantly originating from similar 'average' clouds. These molecular clouds are moderately warm ($T_{\rm kin} \sim 20$ K) and dense ($n(\rm H_2) \sim 10^{3.7}$ cm^{-3}). The LVG estimate of the $X_{\rm CO}$ factor for these clouds of only ~ 0.7 times the galactic value confirms the low value derived from the virial mass estimates.

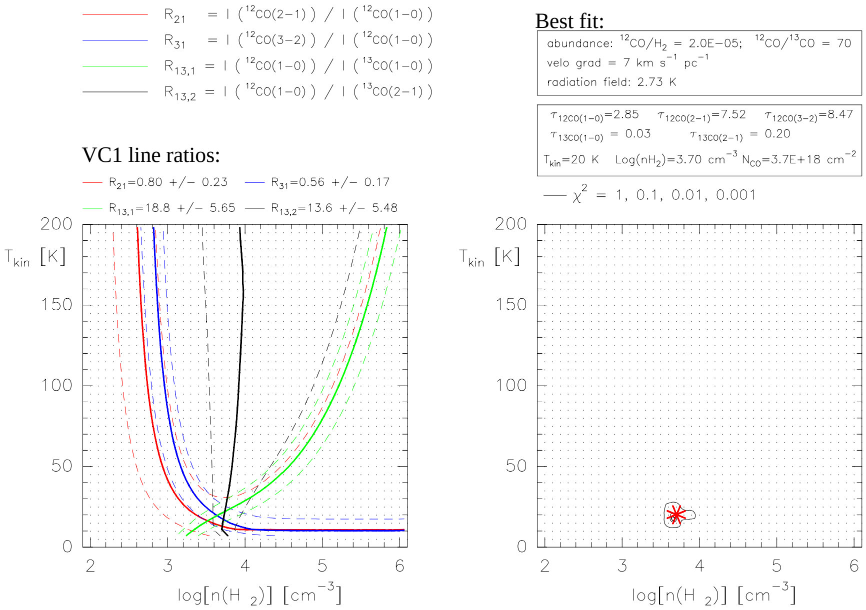

Figure 2: LVG model for one velocity component of the central position. Indicated on the right are the "best fit" LVG solutions for the kinetic temperature and volume density that are compatible with the observed line ratios. A wide range of abundance & velocity gradient models was used.

2.3 The properties of the molecular gas in Haro 2

The quiescent molecular clouds in the central 1 kpc of *this* BCDG have physical properties that are surprisingly close to those of 'normal' galactic clouds. The molecular gas that is directly involved in the ongoing centralized star-formation exhibits only slightly higher densities and temperatures ($n(\rm H_2) \sim 10^{4.0}$ cm^{-3}, $T_{\rm kin} \geq 30$ K). There is also a trend towards lower local $X_{\rm CO}$ values in the center – as expected for heated gas (Maloney & Black 1988, Bolatto et al. 1999; see also Weiß et al. (2000) for a study of the local variations of $X_{\rm CO}$ in M 82). However, the statistics and linear resolution are poor in the case of Haro 2. The CO distribution that extends well beyond the star-forming nucleus and the low $X_{\rm CO}$ values have also implications on the star formation efficiency. The local SFE of 3×10^{-8}/yr is significantly higher than values found for 'normal' spirals or even interacting galaxies. Another surprising result is the relative strength of the CO(3→2) lines that arise from the outer regions of Haro 2. The observed line ratios can not be explained with single phases of the ISM and the excitation conditions in these regions remain puzzling.

3 Discussion

Virial mass estimates and radiative transfer analysis yield consistent, low X_{CO} values for the cloud complexes in Haro 2. Recent X_{CO} studies based on interferometric observations of other metal-poor dwarf galaxies (NGC 4214: Walter et al. 2001; NGC 3077: Walter et al., in prep.) also find low values, clearly deviating from the X_{CO}–metallicity relation (Fig. 3). In some of the low-metallicity systems with detectable CO emission, the CO line does trace the molecular ISM well while it does not in other galaxies of same metallicity. I_{CO} also depends on the heating and cooling of the ISM as well as dust distribution, cloud morphology and cloud size distribution which influence the shielding. Our incomplete understanding of the phases of the dense ISM in dwarf galaxies also manifests itself in the finding of strong CO(3→2) emission from quiescent regions in Haro 2, IC 10, NGC 1569 and NGC 3077 (Walsh et al., in prep.). Obviously CO observations do not unambigously trace the molecular gas in dwarf galaxies. Atomic carbon is expected to reside only in a relatively thin layer around the CO cores and is thus also unsuited as tracer of H_2. More promising are C II observations to trace the entire volume of the molecular phase in star-forming dwarf galaxies with their pervasive radiation fields. However, appart from abundance effects, the interpretation of the C II line strength has to take all the gas heating mechanisms into account. Being one of the major coolants, the C II line is sensitive to effects like cosmic ray heating and heating from soft X-rays. Finding the proper conversion factor of $I_{C\,II}$ to N_{H_2} will be demanding, especially in irregular dwarf galaxies with their inhomogenous ISM and the spread-out star-formation.[1]

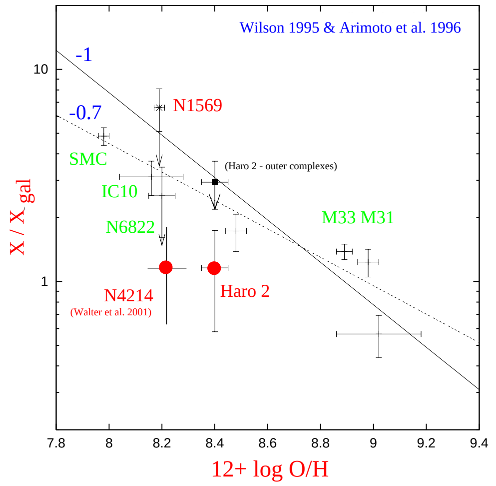

Figure 3: X_{CO}/X_{gal}–metallicity relation for local group galaxies from Wilson (1995); NGC 1569 (*: Taylor et al. 1999); NGC 4214 (Walter et al. 2001) and Haro 2 (filled circles; unresolved CO(1→0) data: square). The solid line gives a theoretically expected linear relation with an exponent of −1 (Bolatto et al. 1999), the dotted line gives the fit of Wilson (1995) with an exponent of −0.67.

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