

A 30m Large Program: The CO Line Atlas of the Whirlpool Galaxy Survey (CLAWS)

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Abstract. Robust knowledge of the distribution, amount, and physical/chemical state of the cold molecular (H_2) gas is key to understanding galaxy evolution. With the help of multi-CO line observations, it is possible to study the molecular gas distribution and disentangle numerous physical and chemical processes that shape and govern the molecular interstellar medium (ISM). For the first time, we obtain full-galaxy mapping data of faint CO isotopologues (^{13}CO , C^{18}O , C^{17}O) at 1mm and 3mm wavelengths across the disk of the nearby spiral galaxy M51. With the help of these CO isotopologues, it is possible to constrain the bulk physical and chemical conditions in the molecular gas. We study potential explanations for why CO isotopologue emission varies. Likely drivers include CO abundance variations due to selective nucleosynthesis and changes in the optical depth. Our analysis concludes that a combination of variation in opacity and relative abundances is the dominant driver for the observed CO isotopologue ratio trends on large (kpc) scales. In contrast, abundance variation due to selective photodissociation and chemical fractionation seem to only play a minor or negligible role on galaxy-wide scales.

1 Introduction

The *CO Line Atlas of the Whirlpool Galaxy Survey* (CLAWS), an IRAM 30-m large program (#055-17), targets the entire molecular disk of the nearby spiral galaxy M51. With the help of the Eight MIXer Receiver (EMIR; [1]), several molecular emission lines, in particular the CO isotopologues, are observed in the 1 mm ($\sim 220\text{--}230$ GHz) and 3 mm ($\sim 90\text{--}110$ GHz) with a total of 149 h (109.2 h on-source time) between 2017 and 2019. We published the survey paper in early 2022 [2]. The galaxy M51 is an excellent candidate for faint CO isotopologue studies: It is relatively nearby ($D \approx 8.6$ Mpc; [3]), oriented edge-on, and the molecular gas dominates the inner $\sim 5\text{--}6$ kpc region [4, 5]. Figure 1 shows the galaxy and indicates the observed IRAM 30m field-of-view. A wealth of ancillary data exists for the galaxy across all wavelength regimes. The key science question of the large program using the 30m observations are:

1. Investigate whether the CO isotopologue line ratios show radial and azimuthal variation across the galaxy's disk. Can we relate any changes to other tracers of galaxy conditions, such as the star formation rate or the distribution of stars and dust?
2. Using the wealth of molecular (CO) line emission, can we determine temperature, column and volume densities, and the CO-to- H_2 conversion factor in and across M51?

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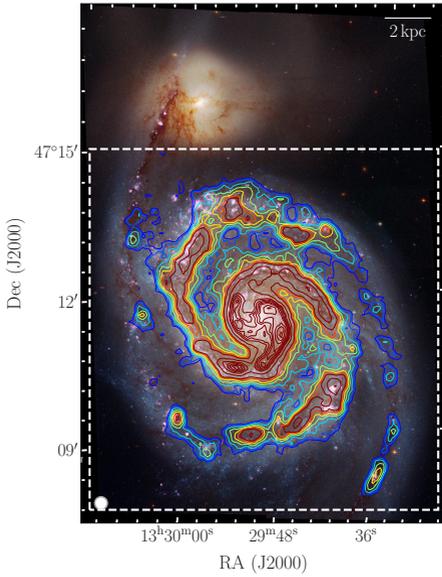


Figure 1. SDSS Composite Image and $^{12}\text{CO}(2-1)$ Contours. The white box outlines the $4.4' \times 4.4'$ map observed with the IRAM 30m telescope as part of CLAWS. The contours illustrate the $^{12}\text{CO}(2-1)$ distribution and highlight various S/N levels from 7 – 70. Figure Credit: taken from [2].

2 Science with Multi-CO Line Ratios

While H_2 is the most abundant molecule in the interstellar medium (ISM), CO and its isotopologues have become a workhorse tracer of the overall molecular gas amount, distribution, and conditions (such as temperature, density, and opacity) [6]. Line ratios from the emission of different species and transitions capture information regarding the ISM environment and conditions. Ratios of the optical thick ^{12}CO line of different $J \rightarrow J-1$ transitions are sensitive to changes in temperature and density of the emitting gas [7]. Furthermore, CO isotopologues provide constraints on optical depth and the abundance of the different species, since ^{13}CO and C^{18}O remain optically thin across most of the galaxy's disk [8]. The different CO isotopologue species originate from various physical and chemical processes, such as selective nucleosynthesis, chemical fractionation, or selective photodissociation. Consequently, trends in abundance variations open a window into studying the enrichment history of the ISM [9].

2.1 The CO Line Ratio R_{21}

The $R_{21} \equiv ^{12}\text{CO}(2-1)/(1-0)$ line ratio has been studied on kpc-scales across M51 before with CO(1-0) observations from the Nobeyama Radio Observatory (NRO) 45m telescope [10] and CO(2-1) data from the IRAM 30m large program *HERA CO Line Extragalactic Survey* (HERACLES; [11]). Already [12] found a clear variation of R_{21} between the arm and interarm region. Using the CLAWS $^{12}\text{CO}(2-1)$ observations in combination with $^{12}\text{CO}(1-0)$ data from PAWS [13], we found larger R_{21} values in the interarm region (the volume weighted average and 16th to 84th percentile range is $\langle R_{21}^{\text{int}} \rangle = 0.95^{+0.21}_{-0.10}$) as opposed to the spiral arm region ($\langle R_{21}^{\text{arm}} \rangle = 0.86^{+0.10}_{-0.07}$). Based on a Kolmogorov-Smirnov test, the R_{21} distributions for arm and interarm are different with a p -value of 4×10^{-10} . Fig. 2 illustrates the result of the binned line ratios by spiral phase. The red and blue bands indicate spiral phases that define the spiral arm. Our finding is in some tension with some of the prior work on this galaxy, e.g. [12], which found exactly the opposite arm-interarm trend. What separates this study is the comprehensive and detailed checking of the contribution of error beams and obtaining even IRAM 30m Director's Discretionary Time (DDT) observations of selected pointings in the arm and interarm regions of M51 [2]. We note that such a finding is actually not unexpected.

Previous studies studying other nearby galaxies also found higher R_{21} values in the interarm region [14–16] and they are not unphysical: Potential explanations could be the presence of diffuse gas at higher excitation temperature and lower optical depths in the interarms which hence leads to brighter CO(2-1).

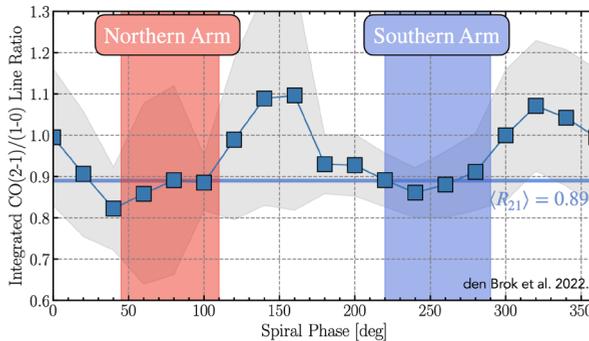


Figure 2. Arm-Interarm Variation of R_{21} in M51. The R_{21} values are binned by spiral phase following the prescription of [12]. The spiral phase values indicating the spiral arms are indicated in blue and red. The 1σ scatter per bin is indicated in light grey. The galaxy-wide CO(1-0) intensity weighted R_{21} value is indicated by the blue horizontal line. Figure Credit: Taken from [2].

2.2 Physical and Chemical Drivers of CO Isotopologue Ratio Trends

Figure 3 shows line ratio trends as a function of the star formation rate (SFR) surface density, Σ_{SFR} , for four selected CO isotopologue ratios. Σ_{SFR} scales with the average gas density and temperature in the molecular ISM [17]. Hence, Σ_{SFR} is a potential proxy of varying environmental conditions. All selected ratios show a clear trend with SFR. Regarding global, galaxy-wide drivers, the observed trends agree with abundance variations from selective nucleosynthesis and changes in the opacity of the CO emitting gas. Since ^{13}CO , C^{18}O , and C^{17}O are optically thin, their variation in the line ratio is mainly driven by changes in their relative abundance. Chemical fractionation which converts ^{12}CO into ^{13}CO is likely not a driver. This process increases the relative abundance of ^{13}CO . Chemical fractionation is more efficient in the colder gas regions, hence at low Σ_{SFR} . So the trend we see in the $^{13}\text{CO}/\text{C}^{18}\text{O}$ ratio would actually be in agreement with the process as the main driver. However, we would expect the opposite trend in $^{12}\text{CO}/^{13}\text{CO}$ line ratio. In contrast, nucleosynthesis could explain the, relatively speaking, higher C^{18}O and lower ^{13}CO abundances and hence the observed trends. In addition, the opacity could vary. This would affect mainly the optically thick ^{12}CO emission line. Similarly to the explanation of the increased R_{21} ratio, the fact that the ratios with $^{12}\text{CO}(1-0)$ in the denominator drop toward higher Σ_{SFR} could indicate the presence of diffuse, more optically thin CO gas in regions with lower SFR. A combination of the above mentioned effects likely drives the overall variation in CO isotopologue line ratios.

We also want to highlight the detection of $\text{C}^{17}\text{O}(1-0)$ across a range of SFRs. The $\text{C}^{17}\text{O}/\text{C}^{18}\text{O}(1-0)$ ratio can trace the primary and secondary processing of oxygen due to nucleosynthesis (similar to $^{13}\text{CO}/^{12}\text{CO}$, however, since ^{12}CO is optically thick, that ratio does not necessarily trace changes in abundance). We find a $\text{C}^{17}\text{O}/\text{C}^{18}\text{O}(1-0)$ ratio similar to the average in the Milky Way solar neighborhood [18]. From nucleosynthesis alone, we would, however, expect an opposite trend. Both isotopologues have very low abundance in general, so selective photodissociation likely plays a more relevant role for this ratio trend. Both

species are not well shielded by the other, more abundant isotopologues (due to differences in the wavelengths of their ultraviolet absorption lines). The $C^{18}O$ isotopologue is more abundant than $C^{17}O$. Consequently, there can be regions within molecular clouds where $C^{18}O$ is still self-shielding, while $C^{17}O$ molecules are photodissociating. This could explain why we see an increase of relative $C^{18}O$ abundance where star formation is more active (and hence the photodissociating radiation field stronger).

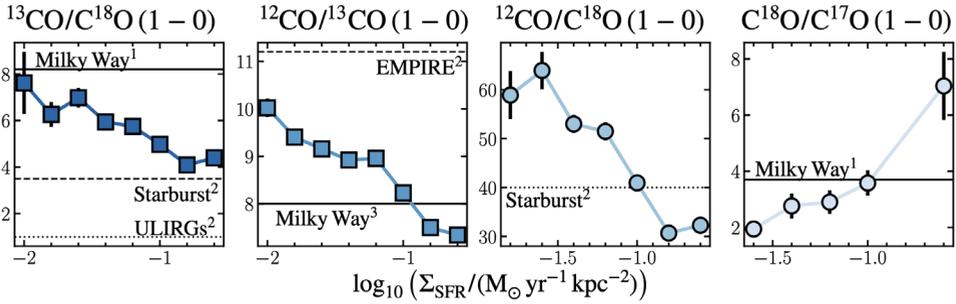


Figure 3. CO Isotopologue Ratio Trends with SFR. The trends are based on stacking by SFR surface density. For reference, average line ratio values for other types and samples of galaxies are indicated. The sources for the average values are: (1) from [18], (2) from [19], and (3) from [20].

3 Conclusion and Outlook

The rich dataset of multi-CO low- J transitions offers the opportunity to study the chemical and physical conditions of the molecular gas across the spiral galaxy M51. We found apparent environmental-dependent line ratio variation, particularly between the arm and interarm regions. We trace that difference to the presence of more diffuse gas in the interarm region. Furthermore, the sense of the observed CO isotopologue line ratio trends agrees with a combination of mainly selective nucleosynthesis and opacity changes of the gas as main drivers. In an upcoming project, we will perform a non-local thermal equilibrium (non-LTE) modeling analysis that will help us obtain constraints on the CO gas temperatures, densities, and the CO-to- H_2 conversion factor.

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