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Small-area molecular structures without shielding

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Abstract. Using the IRAM 30 m telescope two molecular structures have been detected which cover very small areas, $FWHM \leq 1'$. The clouds have velocities of $v_{lsr} \approx 5$ km s^{-1} and linewidth of $\Delta v \approx 0.8$ km s^{-1}; thus they belong most likely to the Milky Way. Applying standard conversion factors one finds that even at the upper distance limit of 2200 pc the structures are low mass objects ($M = (1-6) \times 10^{-4} \left(\frac{d}{100 \text{ pc}}\right)^2 M_\odot$) which are not gravitationally virialized. H I 21 cm line data towards the clouds show no prominent HI clouds. The total H I column densities for both structures are below $N(\text{HI}) \leq 2.1 \times 10^{20}$ cm^{-2}, corresponding to $A_V \leq 0.2$ mag, assuming a standard gas-to-dust ratio. IRAS 100 μm data towards the structures show also only low emission, consistent with low extinction. Unless there is unseen cold dust associated with the structures this shielding is too low for the structures to survive the interstellar radiation field for a long time. The detection of 2 such structures in a rather limited sample of observations suggests that they could be a rather common feature in the interstellar medium, however, so far not recognized as such due to the weakness of their lines and their small extent.

Key words. interstellar medium (ISM): abundances – ISM: clouds – ISM: molecules – dark matter candidates

1. Introduction

H_2 is the most abundant molecule in the universe. Due to its missing dipole moment and its high rotational constant it can only be observed directly in regions with high temperatures. The amount of molecular gas is however reasonably well estimated from observations of the second most abundant molecule, CO, if the metallicity of the gas is about solar (e.g. Dame et al. 2001).

There has been much debate on how much molecular gas can be hidden from the observer in form of small, cold molecular clouds (Pfenniger & Combes 1994; Gerhard & Silk 1996; Walker & Wardle 1998). Pfenniger & Combes argue that the molecular mass can be underestimated in the outer galaxy by as much as a factor 10, if this gas has a fractal structure. Thus, in this form molecular gas could account for all of the missing baryonic dark matter in our galaxy. These so-called "clumpuscules" (Pfenniger & Combes 1994) i) must be small to escape detection, ii) must have high-column densities to survive destruction and iii) must be dense to allow formation of H_2 within a reasonable amount of time. Thus the question on baryonic dark matter in form of small molecular clouds is directly linked to the question on the formation and destruction of H_2 and CO.

In this paper the detection of a previously unobserved component in the interstellar medium is described: molecular structures covering a very small area on the sky located in an environment with very low hydrogen column densities. These objects are ideal targets to study under which conditions CO and H_2 can survive in the interstellar medium. The detection

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was made serendipitously during a search for molecular gas in the tidal arms around the M 81 group of interacting galaxies; the results of this search will be described elsewhere.

2. Observations

The observations were conducted in June 2001 and May 2002 with the IRAM 30 m telescope on Pico Veleta, Spain. In total, four receivers were used, two tuned to the ^{12}CO (1 → 0) line at 115 GHz and two tuned to the ^{12}CO (2 → 1) line at 230 GHz. The observations were done with a wobbling secondary mirror with the off-position separated by 200″ in azimuth from the on-position. The beam size of the telescope is 22″ at 115 GHz and 11″ at 230 GHz. At the beginning of the observing run the setup was optimized for extra-galactic observations; i.e. for each of the 115 GHz receivers a filterbank and an autocorrelator spectrometer with a wide bandwidth and a low spectral resolution were used. At 115 GHz the filterbank had a velocity resolution of 2.6 km s^{-1} and 512 channels, the autocorrelator had 0.8 km s^{-1} resolution and 450 channels.

In total deep integrations on 25 individual positions were made in the tidal arms of the M 81 group of galaxies. During the observations I noticed at four positions some spurious emission- and absorption-like features around $v_{lsr} = 5$ km s^{-1} which were only one channel wide with the setup chosen. To test for a bad channel in the spectrometer or real spectral line the velocity resolution was increased to 0.2 km s^{-1}. Because the features turned out to originate from two real interstellar clouds I started to map the two clouds with a spacing of 20″ between two positions.
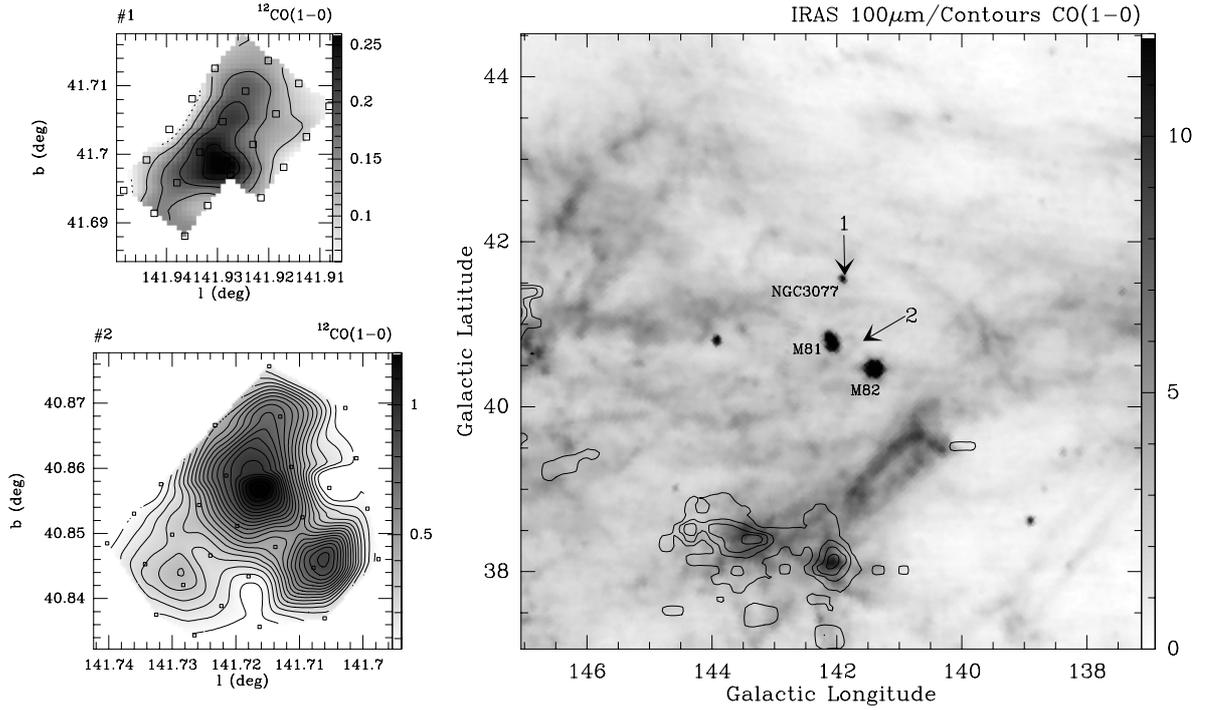
Fig. 1. The small-area molecular structures and their environment. *On the right*: surrounding of the location were the two SAMS have been detected. The grey scale is taken from the IRAS survey at 100 μm; the intensity scale is displayed on the right of the box. Contours represent the CO $(1 \rightarrow 0)$ observations with the 1.2 m CfA telescope observed by de Vries et al. (1987); they are every 0.8 K km s^{-1} starting at 0.8 K km s^{-1}. The point source near SAMS1 is the galaxy NGC 3077, the one near cloud SAMS2 is M 81 and the source below is M 82. Arrows point to the centres of the structures. *On the left*: integrated CO $(1 \rightarrow 0)$ intensity maps of the structures. The lowest contour (dashed) is at 0.06 K km s^{-1} (3σ), step size between following contours is 0.06 K km s^{-1}. Observed positions are marked by open squares.

Table 1. Parameters for the molecular structures.

Number	l (deg)	b (deg)	transition	T_A^* (K)	rms (K)	v_{lsr} (km s^{-1})	Δv (km s^{-1})	$FWHM$ ($''$)	$M(H_2)$ [2] $10^{-4} (\frac{d}{100\ pc})^2\ M_\odot$
#1	141.9275	41.6970	CO $(1 \rightarrow 0)$	0.142	0.008	$+3.92 \pm 0.02$	0.75 ± 0.04	55	2
#1			CO $(2 \rightarrow 1)$	0.034	0.009	$+3.91 \pm 0.08$	0.87 ± 0.15	–	
#2a	141.7154	40.8557	CO $(1 \rightarrow 0)$	0.651	0.014	$+5.38 \pm 0.01$	0.90 ± 0.02	60	6
#2a			CO $(2 \rightarrow 1)$	0.24	0.02	$+5.35 \pm 0.02$	0.85 ± 0.04	–	
#2b	141.7078	40.8446	CO $(1 \rightarrow 0)$	0.32	0.04	$+5.00 \pm 0.03$	0.88 ± 0.09	25[1]	1
#2b			CO $(2 \rightarrow 1)$	0.37	0.08	$+4.88 \pm 0.04$	0.50 ± 0.06	–	

Remarks: Values for T_A^*, rms, v_{lsr}, and Δv are derived from cloud averaged spectra. [1] Unresolved structure. [2] Mass is determined assuming $X_{CO} = 0.6 \times 10^{20}$ cm^{-2} (K km s^{-1})$^{-1}$, d is the distance to the cloud.

3. Results

The incomplete maps are displayed in Fig. 1 together with an IRAS 100 μm map of the surrounding of clouds. Cloud averaged spectra reobserved with a higher spectral resolution are presented in Fig. 2, parameters are listed in Table 1. The structures cover only very small areas on the sky. In analogy to the tiny-scale atomic structures (TSAS) discussed in detail by Heiles (1997) I will refer to them as small-area molecular structures (SAMS) from here on.

SAMS1 appears as single elongated structure whereas SAMS2 can clearly be separated into at least two structures, SAMS2a and SAMS2b. SAMS1, SAMS2a and SAMS2b cover areas of $\geq$9500 arcsec^2, 4800 arcsec^2, and 1800 arcsec^2,

respectively. Due to the incomplete maps this is a lower limit to the total area. Therefore I list the full widths at half maximum, $FWHM$, of the SAMS, which are better determined. These are between 25$''$ and 60$''$. The average CO line temperatures of the SAMS are weak. Their linewidths ($\Delta v \approx 0.8$ km s^{-1}) are lower than for galactic cirrus clouds, for which the mean value is at 2.1 km s^{-1} (Magnani et al. 1996). If the clouds follow the same size-linewidth relation found for many types of molecular clouds, $\left(\frac{\Delta v}{km\,s^{-1}}\right)^2 \approx \frac{FWHM}{pc}$ (e.g. Larson 1981; Heithausen 1996), the clouds must be closer than 2200 pc, i.e. they are galactic objects.

Assuming $X_{CO} = 0.6 \times 10^{20}$ cm^{-2} (K km s^{-1})$^{-1}$ (de Vries et al. 1987) the average H_2 column densities and the masses of the SAMS correspond to $N(H_2) = (0.7-3.7) \times 10^{19}$ cm^{-2} and
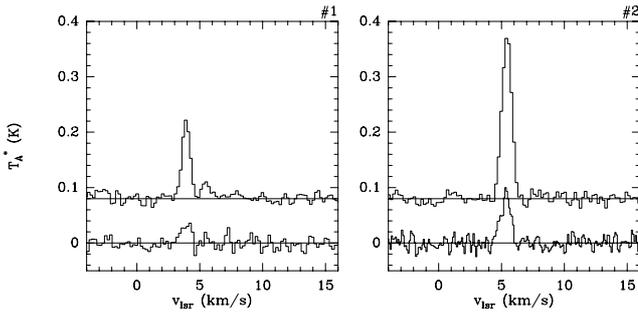
Fig. 2. CO $(1 \rightarrow 0)$ and $(2 \rightarrow 1)$ spectra towards the two clouds. The $(1 \rightarrow 0)$ spectra have been shifted by 0.08 K for better display. The spectra are averaged over the whole cloud.

Fig. 3. Combined Effelsberg and VLA spectrum of the H I 21 cm line towards SAMS1. The dotted line is a fit to the data.

$M(H_2) = (1-6) \times 10^{-4} \left(\frac{d}{100\,\text{pc}}\right)^2 M_\odot$, where d is the distance to the structures. With such low masses the structures are not gravitationally virialized; even at the upper distance limit the virial mass, $M_{\text{vir}} = 210\,M_\odot * \frac{\Delta v^2}{\text{km s}^{-1}} * \frac{FWHM}{\text{pc}} \approx 4\left(\frac{d}{100\,\text{pc}}\right) M_\odot$, is orders of magnitude too large. Note, however, that these parameters are only valid if galactic conversion factors are applicable, which has to be tested by further observations.

The SAMS are also detected in the CO $(2 \rightarrow 1)$ line at various positions. Figure 2 shows the cloud averaged spectra. The corresponding values are listed in Table 1. Due to the undersampling at 230 GHz and the inhomogeneous rms caused by variable summer conditions during the observations, the $(2 \rightarrow 1)$ data provide only limited structural information on the clouds.

The two newly detected structures are located in a low column density environment. Figure 1 gives an overview over the region. The positions are more than two degrees away from the nearest molecular high-latitude clouds studied by de Vries et al. (1987). The level of 100 μm emission observed by IRAS is 2 MJy sr^{-1}. Using the dust emissivity found for galactic cirrus clouds $I(100\,\mu\text{m})/N(\text{H}) = 1.0 \times 10^{-20}$ MJy sr^{-1} cm^2 (Heithausen & Mebold 1989) a total column density of the local gas of $N(\text{H}) = 2 \times 10^{20}$ cm^{-2} is derived on a 4′ scale.

To derive the column density of atomic gas in the direction of SAMS1, published H I 21 cm line observations obtained with the VLA (Walter & Heithausen 1999; Walter et al. 2002) were corrected for missing zero-spacings using data obtained with the Effelsberg 100 m telescope. The resulting angular resolution was 19″ × 16″, the velocity resolution 2.6 km s^{-1}. No evidence for an H I cloud associated with SAMS1 is apparent in the combined VLA/Effelsberg data. The spectrum towards the maximum of SAMS1 shows two velocity components: one broad line coming from the extragalactic tidal arms of the M 81 system and one narrow component coming from local galactic material (see Fig. 3). The local gas component at $v_{\text{lsr}} = 4.0$ km s^{-1} has a H I column density of only $N(\text{HI}) = (1.3 \pm 0.1) \times 10^{20}$ cm^{-2}.

For SAMS2 only information on the local atomic hydrogen on a 9′ scale exist from observations with the Effelsberg 100 m telescope (de Vries et al. 1987). The column density is found to be $N(\text{HI}) = 2.1 \times 10^{20}$ cm^{-2}, consistent with the value derived above from the IRAS data.
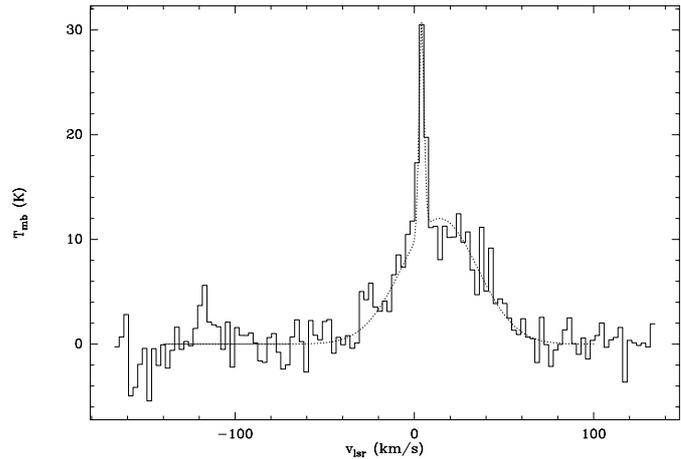
In summary, the column densities along the line of sights towards the SAMS are very low, corresponding to only low visual extinction of $A_V \leq 0.2$ mag, assuming a standard gas-to-dust ratio. One should however keep in mind that with the information presently available, the existence of very cold dust associated with the SAMS cannot be excluded.

4. Discussion

Are we faced with an unknown feature of the interstellar medium or are we just observing the very low mass end of ordinary cirrus clouds? In this section I argue that the structures are different from galactic molecular cirrus clouds in several ways.

The clouds described in this paper are so small and weak that they are missed by any galactic survey conducted so far (e.g. Heithausen et al. 1993; Hartmann et al. 1998). E.g. in the beam of the CfA 1.2 m telescope, the telescope which did most of the inventory of molecular clouds in the Milky Way (Dame et al. 2001), SAMS1 would appear as a 1.6 mK feature, orders of magnitude below the sensitivity of any galactic survey conducted with this telescope.

Besides their compactness SAMS differ from molecular cirrus clouds because they reside in a low column density environment which provides little shielding against the interstellar radiation field. For cirrus clouds the good correlation between CO, H I and IRAS 100 μm data has been used to determine the total hydrogen column density and calibrate the X_{CO} factor (e.g. de Vries et al. 1987). In fact, all molecular cirrus clouds from a large-scale CO survey at high galactic latitudes were seen in the IRAS 100 μm maps, although no one-to-one correlation between CO and the 100 μm intensity exists (Heithausen et al. 1993). For the SAMS described here there is no counterpart in either the IRAS data (though the angular resolution of IRAS might be possibly too coarse to detect them) or in high angular resolution H I data.

Unless SAMS are asoociated with very cold dust which is unseen by IRAS, the extinction of the structures is too low to provide efficient shielding for CO to survive. Modelling of the photodissociation of CO requires visual extinction of ≥ 1 mag or total hydrogen column densities of $\geq 10 \times 10^{20}$ cm^{-2} for the

existence of CO (e.g. Viala et al. 1988; van Dishoeck & Black 1988; van Dishoeck & Blake 1998). Below that limit CO might exist but with a very limited lifetime.

On the other hand, the formation time for H_2 in a diffuse atomic environment is rather long. Pironelli et al. (2000) calculate that for a shielding of $A_V = 1$ mag and $n(H_2) = 100 \, cm^{-3}$ it takes almost 10^8 years for H_2 to built up from atomic hydrogen in large amounts. This time is much longer than the dynamical timescale of the observed structures which is $FWHM/\Delta v \approx 2 \times 10^4 \times (\frac{d}{100 \, pc})$ years.

5. Conclusions

In this Letter I have described the detection of a previously unobserved component of the interstellar medium: small-area molecular structures embedded in a very low column density environment. Aiming at the detection of molecular clouds in extragalactic tidal arms, the observations were not set up to detect local clouds, thus they are unbiased. Based on their location in a low column density environment with insufficient shielding against the interstellar radiation field, the clouds should not exist for very long. Whether sufficient shielding is provided by very cold dust remains to be tested by bolometer observations.

Whether these two structures were picked up just by chance before they are dissolved or whether their detection indicates that H_2 and CO can survive with less shielding than previously adopted is an open question. Because two structures were discovered in a rather limited sample of observations, one could speculate that such structures might be frequent in the interstellar medium. This explanation is also supported by the detection of H_2 in many lines of sight through diffuse galactic clouds in the spectra of distant quasars (e.g. Richter et al. 2001). Due to their weakness and compactness these structures will however be missed by most observations.

Whether or not SAMS are related to the tiny-scale atomic structures (TSAS, Heiles 1997) is unclear. TSAS have been found in H I 21 cm line observations. They are thought to be predominantly made of atomic gas and have sizes of about 25 AU (Diamond et al. 1989). SAMS described here are molecular and have unknown sizes, due to the unknown distance. If we adopt for the moment that they have the same sizes as the TSAS, they would be as close as 0.5 pc. At that distance they would only live for a few hundred years. Whether SAMS

could be related to the sodium absorption line clouds which were found to be non-coincident with H I clouds (Lilienthal & Wennmacher 1990) remains to be tested by sensitive CO observations. If so, these observations will provide the crucial distance information for SAMS.

To estimate the frequency of SAMS, it will be worthwhile to check existing CO observations made towards extragalactic objects for the presence of similar absorption- or emission-like features. Clearly, more information on SAMS are needed before one could draw more firm conclusions on their nature.

References

Dame, T. M., Hartmann, D., & Thaddeus, P. 2001, ApJ, 547, 792
de Vries, H. W., Heithausen, A., & Thaddeus, P. 1987, ApJ, 319, 723
Diamond, P. J., Goss, W. M., Romney, J. D., et al. 1989, ApJ, 347, 302
Falgarone, E., Panis, J. F., Heithausen, A., et al. 1998, A&A, 331, 669
Gerhard, O., & Silk, J. 1996, ApJ, 472, 34
Hartmann, D., Magnani, L., & Thaddeus, P. 1998, ApJ, 492, 205
Heiles, C. 1997, ApJ, 481, 193
Heithausen, A., & Mebold, U. 1989, A&A, 214, 347
Heithausen, A., Stacy, J. G., de Vries, H. W., Mebold, U., & Thaddeus, P. 1993, A&A, 268, 265
Heithausen, A. 1996, A&A, 314, 251
Larson, R. B. 1981, MNRAS, 194, 809
Lilienthal, D., & Wennmacher, A. 1990, A&A, 235, L13
Magnani, L., Hartmann, D., & Speck, B. G. 1996, ApJS, 106, 447
Pironelli, V., Biham, O., Manico, G., Roser, J. E., & Vidali, G. 2000, in Molecular hydrogen in space, ed. F. Combes, & G. Pineau des Forêts (Cambridge Univ. Press), 71
Pfenniger, D., & Combes, F. 1994, A&A, 285, 94
Richter, P., Sembach, K. R., Wakker, B. P., & Savage, B. D. 2001, ApJ, 562, L133
van Dishoeck, E. F., & Black, J. 1988, ApJ, 334, 771
van Dishoeck, E. F., & Blake, G. A. 1998, ARA&A, 36, 317
Viala, Y. P., Letzelter, C., Eidelsberg, M., & Rostas, F. 1988, A&A, 193, 265
Walker, M., & Wardle, M. 1998, ApJ, 498, L125
Walter, F., & Heithausen, A. 1999, ApJ, 519, L69
Walter, F., Weiß, A., Martin, C., & Scoville, N. 2002, AJ, 123, 225