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THE LARGE SCALE MOLECULAR ENVIRONMENT TOWARDS WESTERLUND 1

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RESUMEN

Reportamos el descubrimiento de una cavidad y un flujo molecular en el brazo cercano de Norma alrededor del joven super-cúmulo estelar (SSC) Westerlund 1 (Wd1). La asociación del cúmulo con la cavidad y el flujo molecular es discutida en base al análisis cinemático observado en CO y HI, así como en absorciones observadas de HI. Concluimos que la posibilidad de asociación de Wd1 con la cavidad es alta si ambos están localizados a la distancia de 5.0±0.5Kpc, la cual es un factor 1.4 más lejano que que la más reciente estimación de distancia a Wd1. El gas molecular que rodea la cavidad tiene una masa molecular de 1×10^6 $M_\odot$ y está en expansión a una velocidad de 8 km s^{-1}. La correspondiente energía cinética de expansión es 1×10^{51} erg. El magnetar asociado con Wd1 puede ser la fuente de esta energía.

ABSTRACT

We report the discovery of an outflow and a molecular cavity at the Norma near-arm around the young Super Star Cluster (SSC) Westerlund 1 (Wd1). Association of the SSC Wd1 with the cavity and the molecular out-flow is discussed based on the observed kinematics from CO and HI emission, and also in the observed HI absorptions. We conclude that the possibility of association of Wd1 with the cavity is high if both are located at a distance of 5.0±0.5Kpc, which is a factor 1.4 farther than the most recent distance estimation to Wd1. The shell surrounding the cavity has a molecular mass of 1×10^6 $M_\odot$ and is expanding at a velocity of 8 km s^{-1}. The corresponding kinetic energy of expansion is 1×10^{51} erg. The magnetar associated with Wd1 could be the source of this energy.

Key Words: ISM: jets and outflows — open clusters and associations: individual (Westerlund 1)

1. INTRODUCTION

Westerlund 1 is the most massive stellar cluster detected in the Milky Way disk with a stellar mass of 5×10^4 $M_\odot$. Its age is around 3–4 Myr (Brandner 2008), contains more than twenty Wolf-Rayet stars and one detected X-ray magnetar produced by a very massive progenitor (Muno et al. 2006). Its distance is not yet in consensus but is around 4–5 kpc and then the previous described picture is occurring in approximately ≈6 parsecs. Compared with the nearest Orion Nebula cluster, Wd1 is ten times more massive and include more massive stars, and is one Megayear older. However both have almost the same size implying a bigger concentration in Wd1 and a totally different evolutionary history.

Westerlund 2 is another galactic cluster located in the Milky Way disk, with a stellar mass of 0.7×10^4 $M_\odot$ and younger than Wd1 (2 Myr). Recently the molecular cloud associated to the cluster Westerlund 2 was defined and analyzed by Dame (2007), obtaining a molecular mass of 7.5×10^5 $M_\odot$. There are few stellar clusters detected in the Milky Way disk in this range of stellar masses. However in other galaxies, for example in M82 (Mayya et al. 2008), clusters with theses masses are common.

The distance to Wd1 was revised by Kothes & Dougherty (2007) and its neutral environment was explored. They conclude that Wd1 is at the distance of 3.9±0.7 kpc in the Scuttum-Crux arm, showing absorbtion and kinematics features of a small expanding bubble. However, they didn't discard the possibility that Wd1 is located at the Norma near arm. The distance for this object is relevant in the determination of basic parameters like mass, diameter and consequently evolution.

Following the work of Dame (2007) and Kothes & Dougherty (2007, hereafter K&D) we explore the case for the molecular environment of Wd1 using the Columbia-Calan CO survey (Bronfman et al. 1989). Our approach is exploring the line of sight toward Wd1 in two scales: the central region of few parsecs, and large scales of hundred of parsecs. For the central region we define a square of 16 minutes centered at l=339.55, b=−0.4, and for the large scale we de-

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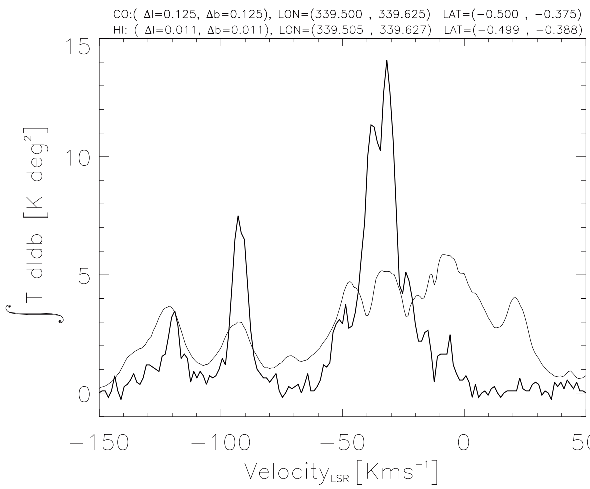

Fig. 1. Integrated spectrum of CO (thick line) and HI (×3) (thin line) toward the central L.O.S. of Wd1. Galactic longitude and latitude ranges are indicated at the top of the figure.

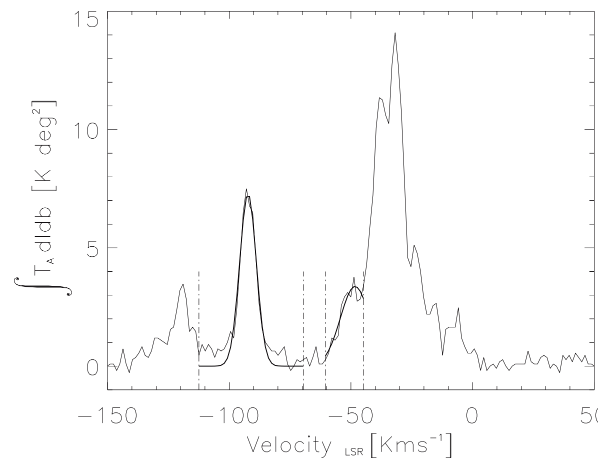

Fig. 2. Gaussian fitting to Norma and Scutum-Crux line features in the integrated spectrum of CO toward the central L.O.S of Wd1.

fine a square of approximately 2 degrees with the same center. The central molecular L.O.S. region is compared with the neutral HI L.O.S. integrated in the same area. For the large scale analysis were used data of 21cm HI line emission from the Milky Way disk survey of McClure-Griffiths et al. (2005). Discussion of the molecular environment of Wd1 is focused in Norma near velocity positions not discarded by K&D and compared with the Scutum-Crux position suggested and analyzed by them.

2. ANALYSIS

2.1. *L.O.S. toward the central region of Westerlund 1*

Using ^{12}CO observations we obtain the molecular line of sight (L.O.S.) toward the central region of Wd1 located at the galactic longitude l=339.55 and the galactic latitude b=−0.4 (Figure 1, thin line). The central region was defined by the 4 beams towards Wd1 (beam size of 0.125 degrees) and its integrated molecular spectra shows emissions at velocities comparable to that obtained of neutral HI emission (Figure 1, overplotted in thick line). This comparison was made using the same region for integration of neutral HI emission.

We perform a gaussian fitting to the Norma line emission feature (Figure 2). Parameters of the adjusted gaussian give us a FWHM of 8 km s^{-1} centered at −92 km s^{-1}. The case for Scutum-Crux feature give us a FWHM of 14 km s^{-1} centered at −48 km s^{-1}. In the Scutum-Crux near arm fitting case, there is superposition of features from the Norma far and near arm positions. All the other line emission features reported by K&D also appear at the CO L.O.S.

2.2. *Molecular emission at Norma near arm toward Westerlund 1*

Using our previous result we integrated the CO emissions for the cube l=[338.750,340.5], b=[−0.875,0.625], v=[−100.0, −85.0] in each range at a time (Figure 3, three quadrants). The specific integrated region appears labeled in the figure for each case, and was remarked with dashed lines and grey fill contours inside the borders. Contours are plotted every 7σ in the plot of velocity integrated emission, and every 3σ for latitude and longitude integrated emission plots.

A brief description of the plot showing the l,b map of integrated velocity (Bottom left), CO emission appears structured in two mayor regions centered at l,b coordinates A=(338.0,−0.2) and a shell like structure centered at (339.7,−0.4) with a diameter of 1.5 deg. Velocity of the structure A is centered at −97 km s^{-1} and displaced in longitude by 1.5 deg. Wd1 is at 10 arcmin of the center inside the molecular shell like structure. North arc emission of the shell structure present a blueshift outflow of −8 km s^{-1} relative to the −92 km s^{-1} LSR velocity of Norma near spiral arm.

Atomic emission from HI data shows very similar kinematics and distribution like that observed in the molecular emission by CO (Figure 4). The CO cavity observed in the velocity integrated map is also well defined in the velocity integrated map of

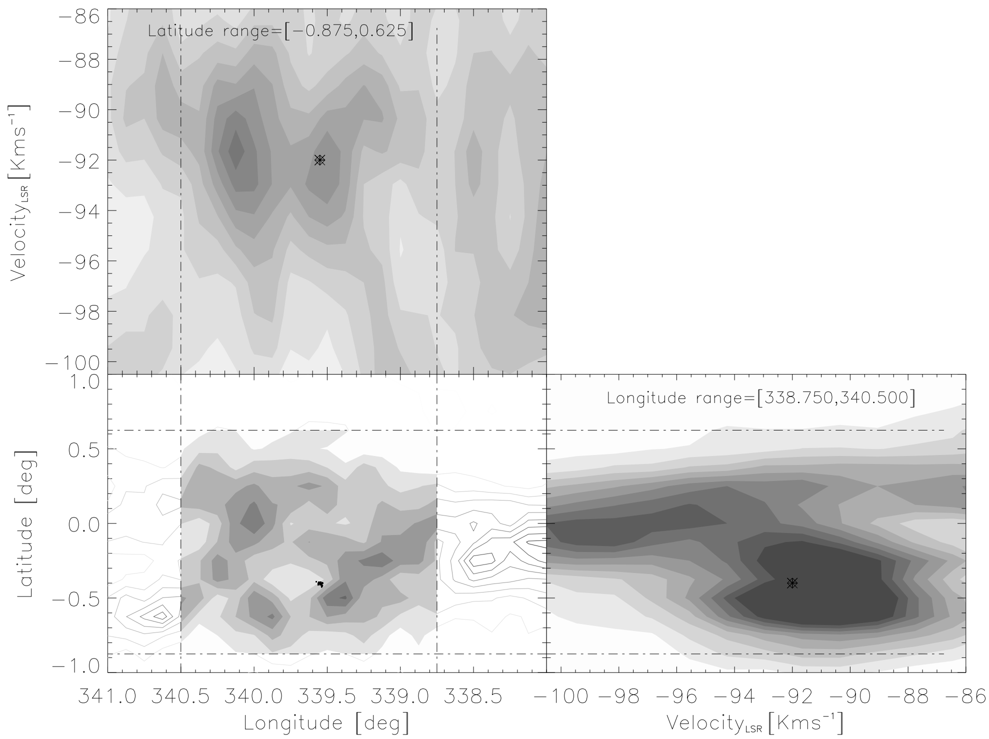

Fig. 3. View of the molecular emission cube at Norma near arm. Top left: Contour plot of latitude integrated emission in the range [−0.875,0.625]deg, contours are plotted every 3σ. Bottom left: Filled contour plot of velocity integrated CO emission in the range $[-85, -100]$ km^{-1}, contours are plotted every 7σ. Bottom right: Contour plot of longitude integrated emission in the range [338.750,340.500]deg, contours are plotted every 3σ. Wd1 position is marked by the massive stars positions from Clark et al. (2005, small dots) and using the velocity of the peak obtained in the gaussian fit at -92 km s^{-1} (previous subsection).

HI. HI lowest integrated emission remarks the inner radius of the molecular cavity observed in CO emission. The 21cm line was not detected in clear absorption at the Wd1 position in nearest channels of the velocity range centered at -90 km s^{-1}. However, we detect a small "depression" with low emission located 2 arcmin south of the central region of Wd1 (l=339.54,b=-0.43) on the channel map at -90.355 km s^{-1}. This depression appears connected with the large scale cavity evidenced by low emission contours and with the presence of the magnetar as is discussed in the next subsection.

2.3. *Star formation regions*

Using data from the literature we project on the channel map at -90 km s^{-1} all the typical objects related with early or massive star formation: HII regions, Wolf-Rayet stars, X ray point sources, pulsars, and previous molecular CO emission lines reported (Figure 5). All the Wolf-Rayet stars reported for this region are members of Wd1 cluster.

Clearly 21cm absorption line for HII regions sources G339.84+0.27, G339.58-0.12, 339.13-0.41, and G338.9-0.1 (K&D) are observed at this velocity channel (Figure 4). Region G339.58-0.12 at the galactic north of Wd1, also appears inside the molecular cavity, but with poor signs of causality. CO contours shows a continuous structure which connect along several star formation regions. This fact suggest the possibility that these regions could be located at that distance in the molecular gas or behind the Norma near spiral arm.

2.4. *Kinetic energy evaluation*

To estimate the kinetic energy involved in the molecular structure, we need the distance to the object. The distance to Wd1 has been calculated with several methods and goes from 1kpc to 6 kpc. The last calculation was using kinematical galactic distances by K&D obtaining 3.9 kpc ± 0.7 kpc. Their determination was refereed to the solar galactic constants V_0=214 km s^{-1} and R_0=7.9 Kpc, a flat rotation curve and circular rotation. This distance and method puts Wd1 at the near side of the Scuttum-Crux spiral arm. Our exploration and discovery of

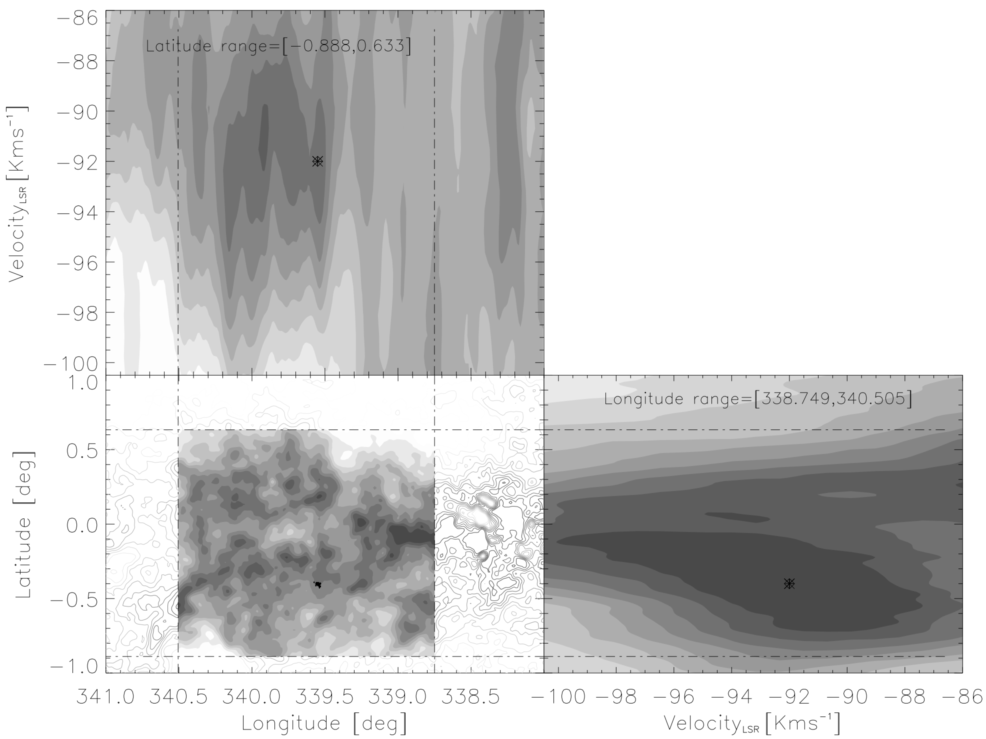

Fig. 4. View of the atomic emission cube at Norma near arm. Top left: Contour plot of latitude integrated emission in the range [−0.875,0.625]deg and every 7σ. Contour plot of velocity integrated HI emission in the range [−85, −100] km^{-1} (bottom left). Bottom right: Contour plot of longitude integrated emission in the range [338.750,340.500]deg and every 3σ. Wd1 position is marked by the massive stars positions from Clark et al. (2005, small dots) and using the velocity of the peak obtained in the gaussian fit at −92 km s^{-1} (previous subsection).

the molecular shell cavity structure at the Norma spiral arm put the possibility of association, Is it a super bubble created by the massive star cluster Wd1?

To explore these ideas we estimate the molecular mass content in the shell. Assuming $N(H_2)/W_{CO} = 1.9\times10^{20}$ cm^{-2} K^{-1} km s^{-1} (Hunter et al. 1989) the molecular gas surrounding the cavity, at the distance of Norma arm of 5kpc (K&D), has a mass of 10^6 $M_\odot$ and an expansion velocity of 8 km s^{-1}, this results in a kinetic energy of 10^{51} ergs, value in agreement to the energy liberated by a SNe.

3. DISCUSSION AND CONCLUSIONS

The CO integrated spectra towards Wd1 shows the same line emission features as that for the observed HI spectra. We put particular attention at velocity positions at Norma (−90 km s^{-1}) near spiral arm. The position of Scutum-Crux (−55 km s^{-1}) was methodically evaluated by K&D.

Wd1 is the most massive star cluster in the Milky Way, it has associated the highest number of Wolf-Rayet stars discovered in a star cluster, and a magnetar. Their age is around 4Gyr delated for the presence of post main sequence stars and the magnetar. Evidence of interstellar molecular medium around massive star clusters, like Wd1, is shown for example towards the younger star clusters Westerlund 2 (Dame et al. 2007). Comparison in some general properties for this two star clusters are shown in Table 1.

TABLE 1

COMPARISON FOR TWO MASSIVE STAR CLUSTERS

Parameter	Westerlund 1	Westerlund 2
Stellar Mass ($M_\odot$)	1×10^5	0.7×10^4
Age (Myr)	3.6 ± 0.7	1–3
Distance (kpc)	5.0 ± 0.5	6 ± 1
Molecular Mass ($M_\odot$)	1×10^6	7.5×10^5

Our analysis of the molecular and atomic environment at large scales towards Wd1 at Norma near spiral arm position, shows a molecular cavity with

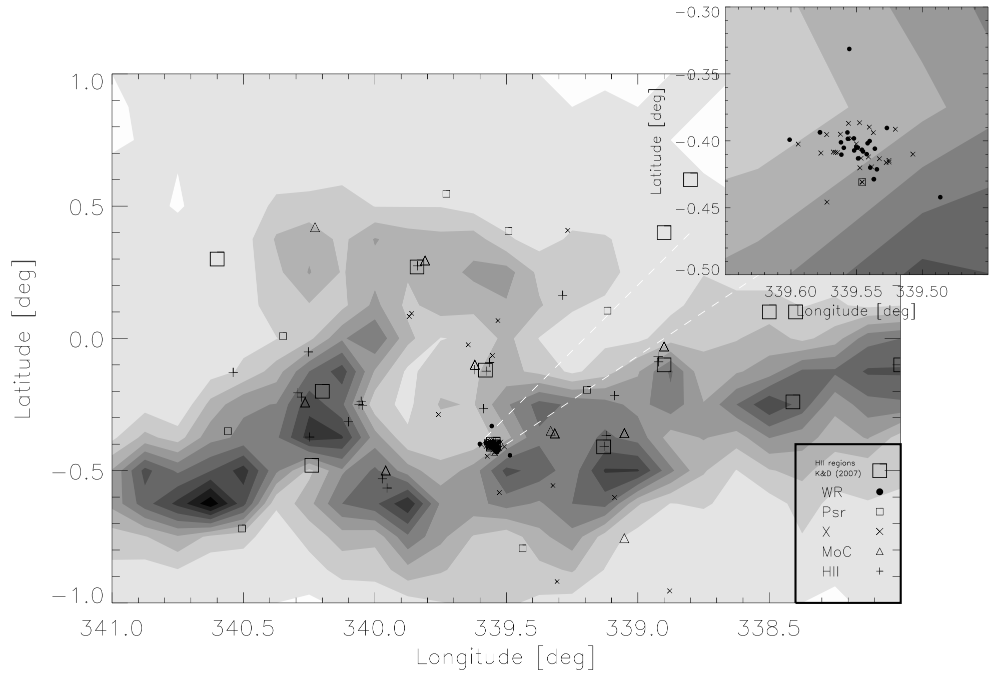

Fig. 5. Overplotted on the CO channel map at -90.355 km s^{-1} we show the HII regions from Kothes & Dougherty (2007, marked with large squares), Wolf-Rayet stars (black dots), molecular clouds (triangles), HII regions (plus signs), pulsars (small squares) and X-ray punctual sources (X signs). CO contour levels are plotted every 3σ.

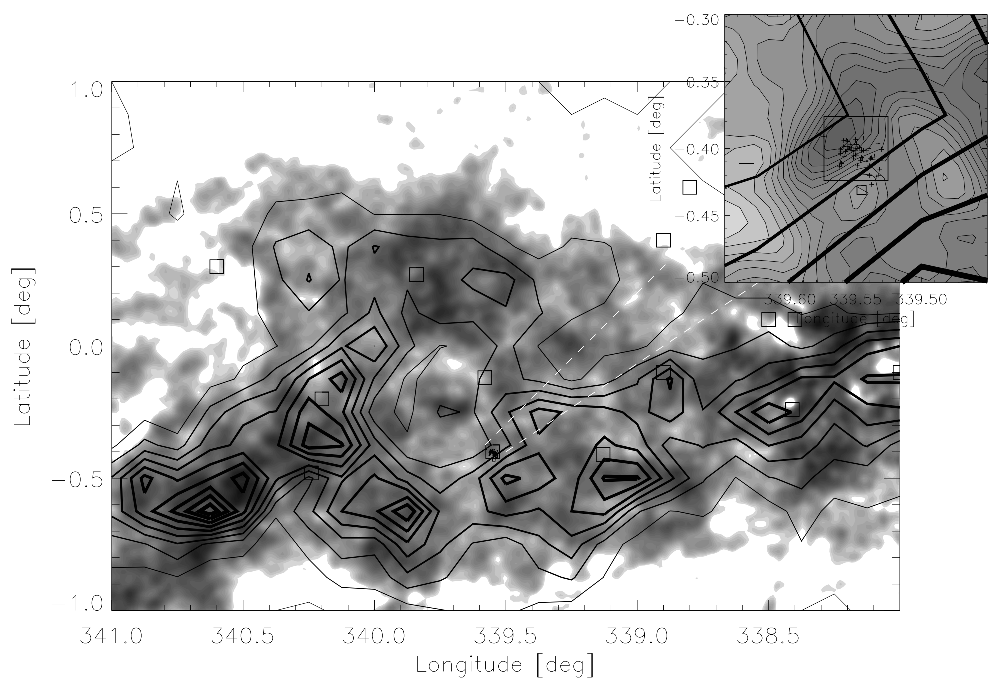

Fig. 6. Antenna temperature of HI at channel -88.213 km s^{-1} and overplotted CO emission at channel -90.355 km s^{-1}. CO contour levels are plotted every 3σ, HII regions from Kothes & Dougherty (2007) are marked with squares. It is inserted a zoom view of the Wd1 position. In the insert we plot (small plus signs) the massive stellar component of Wd1 analyzed by Clark et al. (2005), and also the associated pulsar (Muno et al. 2006) is marked by the smallest square.

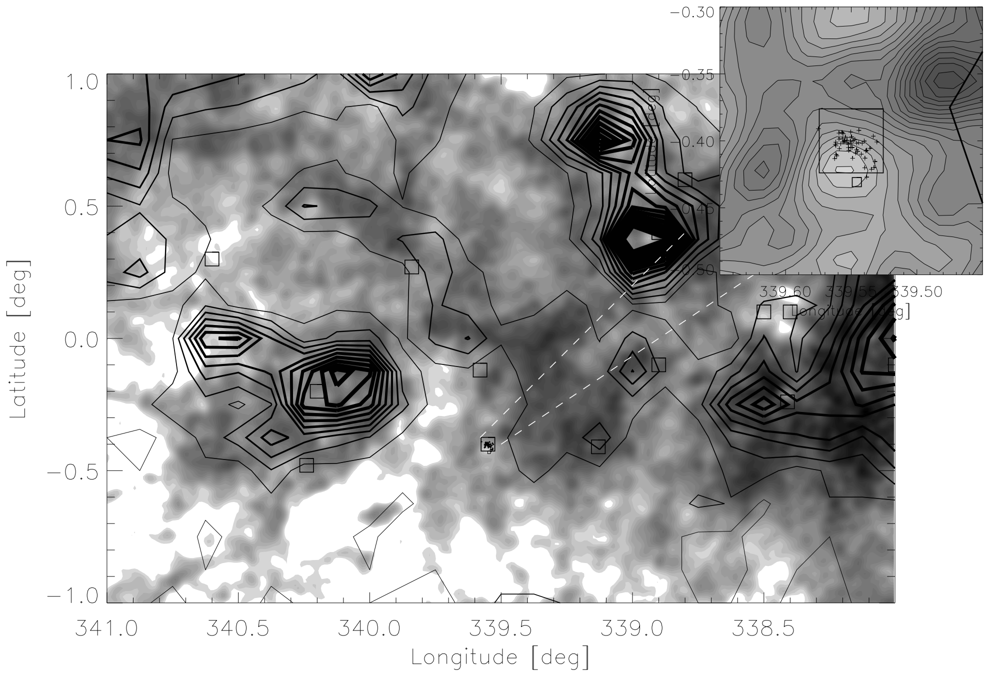

Fig. 7. Antenna temperature of HI at channel -55.236 km s^{-1} and overplotted CO emission at channel -55.244 km s^{-1}. CO contour leves are plotted every 3σ HII regions from Kothes & Dougherty (2007) are marked with squares. It is inserted a zoom view of the Wd1 position. In the insert we plot (small plus signs) the massive stellar component of Wd1 analyzed by Clark et al. (2005). Also the associated magnetar (Muno et al. 2006) is marked by the smallest square.

its Northern part in expansion towards us. At small scales, there is a perfect coincidence with the magnetar position and the "depression" observed at Figure 6 insert. Comparatively, the molecular environment at Scutum-Crux near spiral arm position, at large scales, does not present a clear molecular structure associated with the presence of the massive star cluster Wd1, but also presents a "depression" associated with the magnetar.

Mass calculations of the molecular gas surrounding the cavity (torus) at Norma near position, accounts for approximately 1×10^6 $M_\odot$. Kinematical distance to Wd1 is 5.0±0.5 kpc, which is a factor of 1.4 farther than the value determined by K&D and used in other studies to determine age and mass of stellar population (Brandner et al. 2007). The diameter for the torus at this distance, is approximately 100 pc. Finally, the molecular mass and the inferred size of Wd1 using our revised distance, compares well with the corresponding values for molecular environments around young massive star clusters like Westerlund 2.

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