*Hunt for Molecules*
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# HIGH VELOCITY CLOUDS: NEW HUNTING GROUNDS FOR MOLECULES?

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**Abstract.** A new perspective on HVCs has been recently opened with the first detection of far-IR dust emission from an HVC with the Spitzer Space Observatory. We argue that the dust emission implies a gas column density much larger than that derived from HI observations and thereby that most of the HVC gas mass may be in molecular clumps. These clumps are required to have a small surface filling factor to have escaped detection in UV and millimeter spectroscopy observations. This interpretation of the dust emission motivates a new attempt to detect CO in emission in HVCs.

## 1 Introduction

Since their discovery in HI observations, High Velocity Clouds (HVCs) keep being the puzzling targets of numerous studies and oberving programs. It is now widely considered that a large fraction of them (those not associated with the tidal interaction between the Milky Way and the Magellanic Clouds - i.e. The Magellanic Stream) might be infalling clouds fueling the Galaxy with low metallicity gas. Such an infall of gas is required to account for the distribution of stellar metallicities with age (e.g. Wakker et al. 1999) and to maintain bars in galaxies (Bournaud and Combes 2002); it will also fuel star formation. Within this perspective, HVCs are seen as local analogs of the Lyman limit absorbing clouds observed against distant quasars (Blitz

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et al. 1999). This hypothesis received support from ultraviolet observations showing that HVCs have a subsolar metallicity (Wakker et al. 1999) and a D/H ratio compatible with primordial abundances of deuterium (Sembach et al. 2004),

HVCs have now been observed at a range of wavelengths (see van Woerden et al. 2004 for a thorough review). HI and $H_\alpha$ emission together with numerous absorption studies carried out with FUSE show that HVCs are multi-phase systems comprising neutral and ionized, warm and cold, gas but there is no or little evidence for molecules. Molecular gas has been unsuccesfully searched in emission with the Kitt Peak teslecope (Wakker et al. 1997) and in absorption with the SEST and the IRAM interferometer (Combes and Charmandaris 2000). Two detections of $H_2$ in absorption with FUSE have been reported but the column densities are much lower than those of HI (Richter et al. 2001). If molecular gas is present in large amounts in HVCs, it must be hidden in a fractal structure with a low surface filling factor as what has been proposed for the external parts of galaxies by Pfenniger and Combes (1994). The recent detection of a High Velocity Cloud in the infrared supports this possibility.

## 2 Dust Emission

Lockman and Condon (2005) have recently published high quality HI observations made with the Green Bank Telescope towards the high Galactic field selected for the First Look Extragalactic Survey carried out with the Spitzer Infrared Space Telescope. We have used these HI data to make maps of the different velocity components in this field including high velocity gas at -180 km/s which is part of one of the largest high velocity gas structure in the sky known as Complex C. We have correlated the HI maps with the diffuse emission present in the Spitzer and IRAS images (Miville Deschênes et al. 2005). The surprising result of this correlation analysis is that we undoubtly detect diffuse IR emission from the high velocity gas. Our study improves on the first unsuccesful attempt to find an IR counterpart to HVCs in the IRAS images (Wakker and Boulanger 1986) in two ways. The quality of the Green Bank data is far superior to that of the HI survey data used in the Wakker and Boulanger paper and we used Spitzer and newly processed IRAS images(Miville Deschênes and Lagache 2005) which provide higher sensitivity to faint diffuse emission.

The dust spectral energy distributions (SEDs) of the local, intermediate velocity and high velocity gas are shown in Figure 1. The HVC dust emission per HI column density is much smaller than that measured for the local gas at $\lambda < 100\mu m$ but almost comparable at $160\mu m$. The dust in the HVC is found to be colder ($T_d$=11 $\pm$ $3K$, see Miville Deschênes et al. 2005 for a discussion on error bars) than in the Solar Neighborhood ($T_d$ = 17.5 K). The difference in temperature can be accounted for by a lower radiation field in the HVC than in the Solar Neighborhood due to its distance to the Galaxy (Wakker and Boulanger 1986 - a lower distance of 4 kpc to complex C has been derived from absorption studies towards halo stars) and local extinction if the dust emission is arising from high column density clumps. Taking into account the difference in temperature, we derive from the HVC SED a dust optical depth per HI a factor $> 1.6$ ($3\sigma$ lower limit) larger than that for the local gas. This value larger than 1 is opposite to metallicity estimates. Wakker et al. 1999 measured the metallicty in Complex C to be 1/10 Solar; higher values have been reported for other sight lines but all values are lower than 1/3 Solar.

The dust optical depth per hydrogen is the product of the dust opacity per unit dust mass times the dust-to-gas mass ratio. For given depletions of heavy elements, the dust-to-gas mass ratio is proportional to the metallicity. Combining the lower limit on the dust opacity per HI with the upper limit on metallicty we get a lower limit on the dust opacity per unit dust mass a factor 5 higher for the HVC than for the local gas. An alternative interpretation is that the dust opacity per unit dust mass are the same for the HVC and local gas, and that the HI accounts for less than 20% of the total gas column density. The column density of photo-ionized gas at the surface of HVCs is estimated to be $(2-4) \times 10^{19}$ cm$^{-2}$ in Complex C (Wakker et al. 1999), a value comparable to HI column densities. If we assume that HVC and Galactic dust have similar far-IR, we thus arrive to the conclusion than HI and HII together account for less than 40% of the total gas column density and that more than 60% of the HVC gas is in the form of $H_2$. This interpretation of the infrared observations calls for a new search for molecular gas in HVCs.

## 3 Looking for molecular gas

If molecular gas is present in significant amounts in HVCs it must be hidden in clumps with a low surface filling factor to have escaped detection

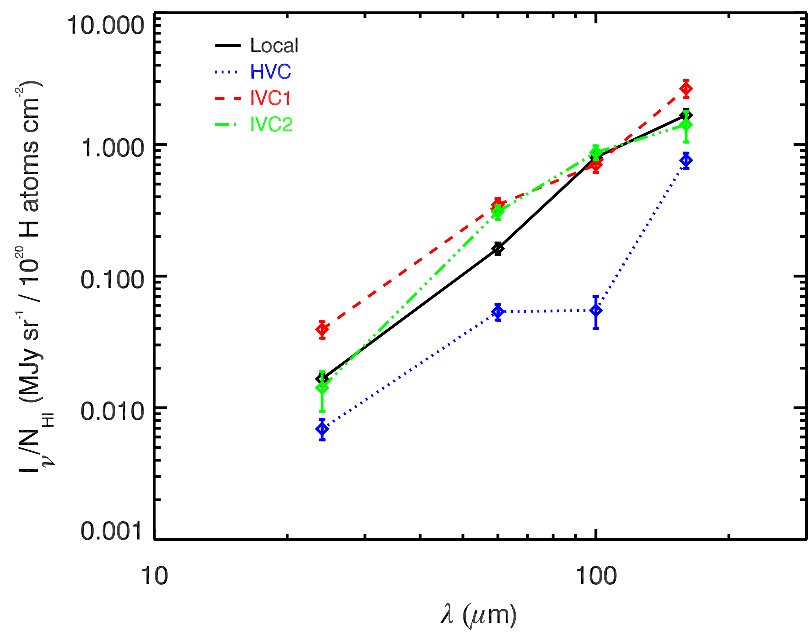


**Fig. 1.** Results of the IR-HI correlation analysis between the Green Bank and infrared (Spitzer+IRAS) images. The IR emission per HI column density is shown for the local, intermediate velocity clouds (IVC1 and 2) and the high velocity cloud present in the field (Miville Deschenes et al. 2005).

in absorption studies. The Helix nebula provides a spectacular example of an astrophysical environment where molecular matter accounting for a major fraction of the mass lies into clumps with a small volume filling factor (Meixner et al. 2005). In the Helix, the clumps are thought to result from instabilities in an expanding ionization front (Capriotti 1973). For high velocity clouds, the clumps could result from the compression and fragmentation of the infalling gas in its dynamical interaction with Galactic halo gas. Within this perspective, a nearby example of the plausible morphology of high velocity clouds might be provided by images of the Draco molecular cloud (Odenwald and Rickard 1987)

To define an observing program, we quantified how molecular matter may be hidden with a simple model of gravitationally bound clumps. We computed the mean column density of the clumps assuming virial equilibrium between the clump kinetic energy (thermal+turbulent) and the gravitational energy. For the thermal energy, we used a 10 K temperature; for the turbulent energy we assumed that the Galactic scaling law relating turbulent velocities in molecular gas to sizes applies to HVCs. We assumed a distance of 5 kpc to Complex C, a little beyond the lower limit (4kpc) set by absorption studies. In Figure 2, we show the mean column density of clumps versus their diameter. To estimate the CO emission of these clumps, we used the most recent version of the Meudon (Le Bourlot et al. 1993, http://aristote.obspm.fr/MIS/) model of photo-dissociation regions. We run the model for a UV radiation field and metallicity 1/10 the Solar Neighborhood values taking into account both the distance to the Galaxy and the metallicty as measured in absorption studies. For these parameters the CO emitting layer is located at a column density $N_H \sim 10^{22}\mathrm{cm}^{-2}$ into the cloud where the gas temperature is 10 K. The CO(2-1) brightness for a clump with a column density $>$ a few $10^{22} cm^{-2}$ was computed to be $1\times10^{-10}\mathrm{W\,m^{-2}\,sr^{-1}}$ which corresponds to a brightness temperature of 10 K for a line width of 0.9 km $s^{-1}$.

The 30m IRAM telescope with HERA and VESPA in the CO(2-1) line can greatly improve on the Kitt Peak observations of Wakker et al. (1997) by providing a gain by a factor 25 in beam dilution. We have thus proposed to use the 30m to map in CO(2-1) an area corresponding to one Green Bank Telecope HI beam towards the HVC detected with IRAS and Spitzer. Within the simple model of spherical clumps, the detection limit of the proposed observations correspond to clumps of 0.1 pc diameter with column densities $\sim 7\times10^{22}\mathrm{H\,cm^{-2}}$, filling only 10% of the IRAM beam (Fig. 2). The HVC HI column density is $6\times10^{19}\mathrm{H\,cm^{-2}}$. Based on the interpretation of the dust detection proposed at the end of Sect. 2, the hydrogen column density in $H_2$ is at least three times larger, i.e. $> 2\times10^{20}\,\mathrm{H\,cm^{-2}}$. For the 0.1 pc clumps, the surface filling factor will thus be $> 3\,10^{-3}$. The area to be mapped will be sufficiently large to encompass a significant number of clumps. Observations will be obtained in February 2006.

## References

Blitz, L. et al. 1999, Ap. J. 514, 818

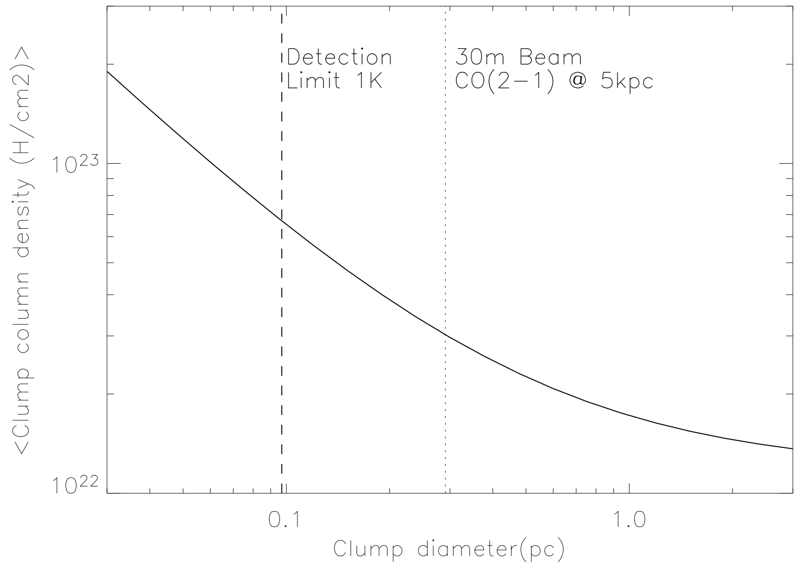


**Fig. 2.** Mean column density of gravitationally bound clumps versus clump diameter. Observations to be done with the 30m IRAM telescope will have the sensitivity to detect clumps with diameters as small as 0.1 pc at 5 kpc.

Bournaud, F., Combes, F. 2002, A& A 392, 83

Capriotti, E. R.1973 Ap. J. 179, 495

Combes, F., Charmandaris, V. 2000, A& A 357, 75

Lockman, F.J., Condon J.J. 2005, A. J. 129, 1968

Meixner, M., McCullough, P., Hartman, J., Son, M., Speck, A., 2005AJ....130.1784

Miville Deschênes M.A., Boulanger, F., Reach, W., Noriega Crespo, A. 2005 Ap. J. 631, L57

Miville Deschênes M.A., Lagache, G. 2005 Ap.J.S. 157, 302

Odenwald, S. F.,Rickard, L. J., 1987 Ap. J. 318, 702

Pfenniger, D. and Combes, F. 1994, A& A 285, 94

Richter, P., Sembach, K. R., Wakker, B. P., Savage, B. D. 2001, Ap.J. 562, L181 van Woerden, H., Wakker, B. P., Schwarz, U.J., de Boer, K.S. 2004, High Veloicty Clouds (Dordrecht: Kluwer).

Sembach, K. R., et al. 2004, Ap. J. Suppl. 150, 387

Wakker, B. P., Boulanger, F. 1986, A& A 170, 84

Wakker, B.P., Murphy, E.M., van Woerden, H., Dame, T.M. 1997, Ap.J. 488, 216

Wakker, B.P. et al. 1999, Nature 402, 388

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