Peering into HVC: There is more to just high velocity

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In this project using the HI 4π Survey (HI4PI) survey data observed by the Effelsberg 100m RT and the ATNF Parkes 64-m telescope, I will analyze high-velocity clouds. These fast-moving clouds do not engage in the galactic rotation and account for a large amount of baryonic matter in the galactic halo extensively contributing to the star formation rate. My analysis aims to filter out these clouds from the data cube allowing me to study it's multiphase structure in which hot and cold phases coexist within the same cloud [7]. Using the equations of virial equilibrium between the shells of the gas and the T_6 parameter [7] I derived a distance of 67.84 kpc to one of the HVC. These clouds exist in a wide range of sizes varying from 1-2 pc to 2-15 Kpc. I was able to derive a mass of 1.47×10^7 M_{sun} for the cloud which seems to be a gravitationally bound system.

I. INTRODUCTION

Abundantly found in the central molecular zone (CMZ) high-velocity clouds do not engage in the differential galactic rotation, rather have anomalous velocities. Although there have been multiple revisions on the actual definition of high-velocity clouds, the current one [6] states that they have $|V_{dev}| > 90$ km/s, where V_{dev} (Deviation velocity) is the difference between the observed velocity of the gas and the maximum velocity of differential galaxy rotation. However, it is worth mentioning that the current HVC catalogs don't follow this definition strictly. In general, we can simply define them as neutral hydrogen clouds with V_{LSR} >90 km/s.

These fast-moving clouds are important not only because they account for a large amount of baryonic matter in the galactic halo but also extensively contribute to the star formation rate (SFR) of the galaxy. In this project, I will try to locate these clouds from the All-Sky HI survey(HI4P1), discuss their physical properties, comment on their origin and finally try to show how they contribute to star formation in galaxies. [1]

The origin of high-velocity clouds is still not known completely. No one theory explains all the HVCs in the galaxy. The leading candidates currently are galactic fountain, materials lost from dwarf galaxies, and the ancient remnants of galaxy formation.

The Galactic fountain model[2] is one of the leading theories currently and can be summarized as follows:

- Clouds of neutral hydrogen can condense from hot dynamic corona above the plane of the galaxy.
- Supernova-heated gas that arises above the disk must either flow outward as wind or remain bound to the Galaxy in a dynamic corona in which gas is constantly in motion.
- Gas continuously entering the corona from the disk rises (in Z) and outward (in ω) in an attempt to reach static equilibrium with the corona.
- Clouds form toward the top of the corona at about one density scale height because thermal instabilities grow most rapidly there.
- After formation, clouds fall ballistically toward their point of origin.

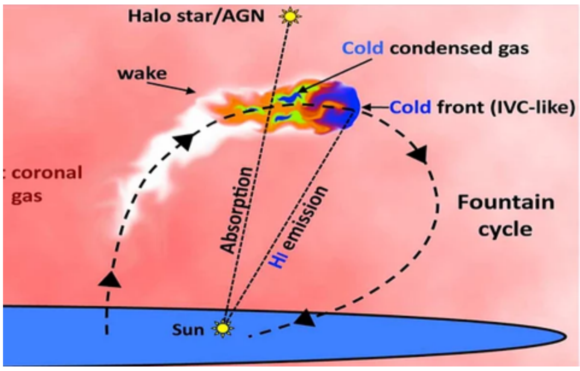

FIG. 1: sketch of a fountain cloud, ejected from the disc by supernova feedback and interacting with the hot gas in the corona. Credit : Filippo Fraternali[4], University of Groningen

Tidally stripped gas streams from dwarf galaxies are also thought to contribute towards these high-velocity clouds. Once these streams of gas are not gravitationally bound to these dwarf galaxies they start interacting with the gaseous environment of the local group. The prevailing model for the origin of the Magellanic Stream is by tidal gravitational interaction with the Milky Way, as the Magellanic Clouds make a close passage. Such tidal interactions lead to both a leading and a trailing feature. This process also contributes significantly to the stellar content of the Galactic Bulge and star formation.

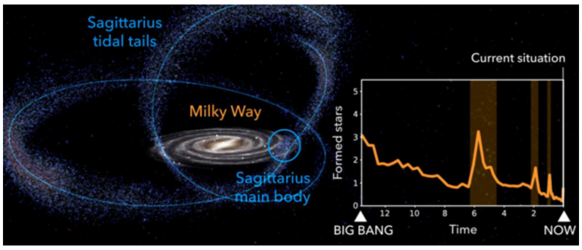

FIG. 2: Left: Artist's impression of the current interaction between the Sgr dwarf galaxy and the Milky Way. Credit: Gabriel Pérez Díaz, SMM (IAC). Right: Detailed evolutionary history of Milky Way star formation enhancements can be seen

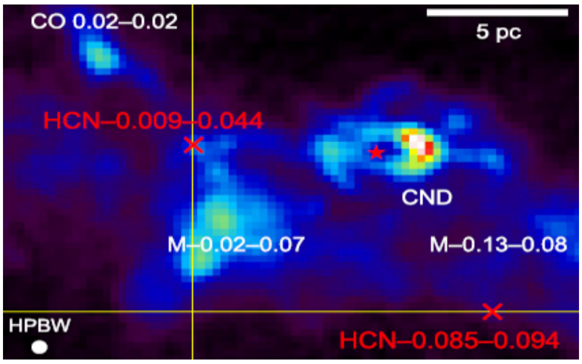

FIG. 3: CO and HCN HVCs spreading over just 1 2 pc, Takekawa et al[5].

The ancient remnants of galaxy formation model involve gas that never formed into galaxies. The high-velocity clouds are strewn across the Local Group at distances of hundreds of kiloparsecs. The total HI mass in this model is comparable to, if not higher than, the gaseous mass within galaxies, suggesting that the clouds may be cosmologically significant. The model's main prediction, their huge distances, has yet to be proven, but research into the matter is ongoing.

A lot of the recent studies on these clouds further subcategorize them into ultra-compact high-velocity clouds meaning they spread over just a couple of parsecs (d 1-2 pc). This goes on to show that these clouds have a wide range of size the larger ones spanning between 2-15 Kpc.[5, 6]

To explain their high-velocity dispersion it is proposed that these clouds are driven by the plunge of an invisible compact object such as inactive isolated black holes. What makes this theory interesting is that these high-velocity clouds can thus work as tracers to the inactive isolated black holes. On the other hand, some studies suggest that it might not be any black holes at all, rather supernovae explosions from nearby dying stars. So there is still no conclusive explanation about their high-velocity dispersion.[5, 8]

There is still not much clarity over what surrounds the HVCs. Some HVCs are found within a few kiloparsecs of the Galactic Disk, according to UV and optical absorption-line research. Some clouds, on the other hand, could be up to a megaparsec away from the Galaxy. HVCs are one of the few probes of the gaseous Galactic Halo and the gas between the galaxies of the Local Group at these distances. A lot of facts about temperature, density, internal structure, and velocity widths of the HVCs are still not known in the halo of the Milky Way.

In this project using the HI4PI survey spectral cube data[1], I will analyze one of the HVC clouds by filtering them out according to their velocity widths and show their multiphase comet-like structure. Using Wolfire's parameter and virial equilibrium equations I have calculated the distance to one of these clouds and its current trajectory. My analysis also shows that this cloud is almost 10 million solar masses with a radius of 848 pc.

II. DATA USED

I used data from a spectral observation of the 21 cm line as FITS files for this analysis[1]. The brightness temperature values are represented as 266 × 266 × 933 elements in the data cube. The location in the sky (latitude and longitude) is represented by the surface of 266 × 266 elements, while the velocity recorded by the Doppler effect in each pixel is represented by 933 elements in the other direction, namely "depth" of the hyperspectral cube. The brightness temperature itself does not carry a physical meaning. However, we can estimate the mean integrated column density from the brightness temperature with Equation 1.

$$\frac{\langle N_{HI}\rangle}{cm^{-2}} = 1.82243 \times 10^{18} \times \int_{-\infty}^{+\infty} \left(\frac{T_b(v)}{K}\right) d\left(\frac{v}{km.s^{-1}}\right) \tag{1}$$

where T_b is the mean brightness temperature, and dv is the spectral resolution.

III. METHODOLOGY

Firstly, I will try to visualize the entire data cube through the spectral cube astropy function and create moment maps of the data. Moment maps are a useful analysis tool to study data cubes. In short, a moment is a weighted integral along an axis (typically the Spectral Axis) that can give information about the total Intensity

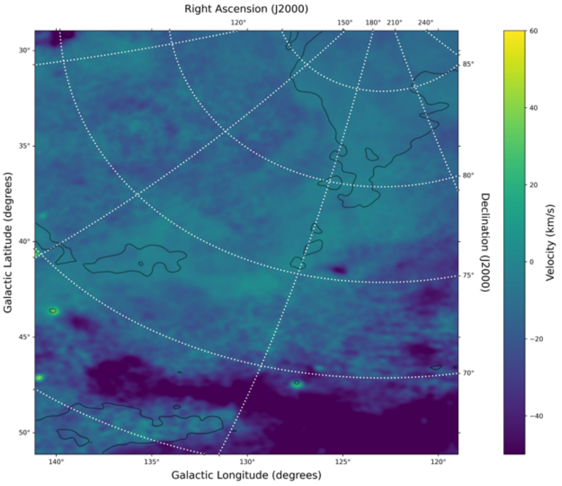

FIG. 4: Moment map(0 and 1) of the data cube

(or column density), mean velocity, or velocity dispersion along lines of sight.

This moment map helps me to spot the high-velocity clouds as a function of their velocity width. I can now clearly see two high velocity patches in my entire map.

After spotting the clouds a spectral slice of the same was taken along its longitude which shows its LSR (local standard of rest) velocity.

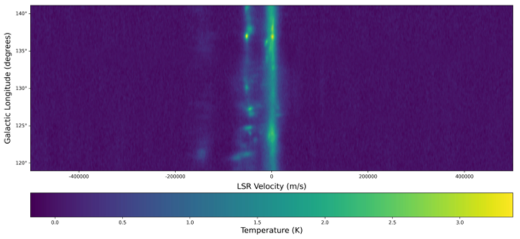

FIG. 5: Longitude vs LSR(local standard of rest) velocity (a data slice along single axis)

The total integrated column density for each space element was determined first. The total H2 column density is a fundamental quantity used to determine a variety of properties that are important for studies of interstellar medium (ISM) and star formation. Since we look at the 21 cm line from all over the Milky Way, we take into account that the emission generated all over the observed solid angle, making it difficult to discriminate between the Galaxy and other objects moving out/towards it. The plot shown was obtained using the data as it is. [3]

If we check the value of Tb along all of the pixels, we would always find a big peak centered at 0 km/s. Since we are measuring only the speed with which the objects move along our axis of sight, we can assume that it corresponds to everything moving along the Galactic disk, just like us. However, a second peak would appear at around -200 km/s.

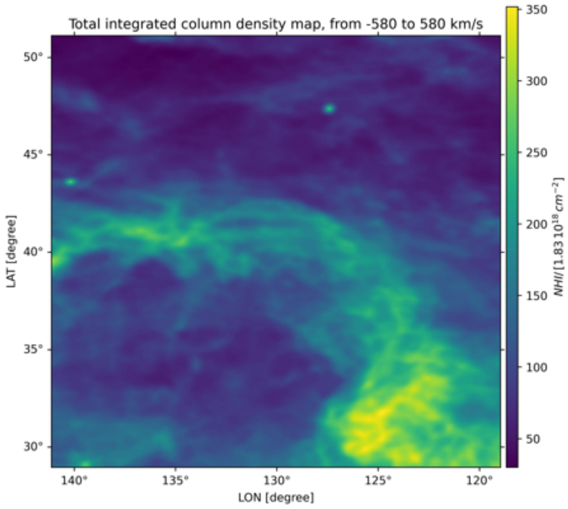

FIG. 6: Total integrated column density map

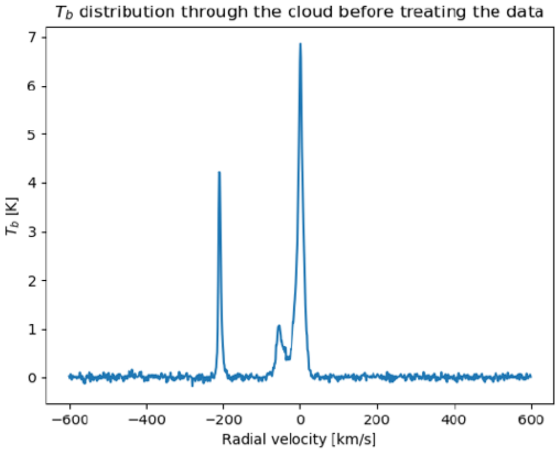

FIG. 7: Tb distribution through the cloud

Considering that the two peaks are located only on specific parts of the spectrum, and a few other approximations due to the nature of the cloud, we can say that the object is moving "independently" of the rotation of the Galaxy, and thus we assume that everything between a range, from -225 to -185 km/s, in this case, is enough to separate such anomalous object from the background, which will turn out to be our High-Velocity Cloud (henceforward, HVC). Now, recalculating the mean integrated column density for the above-mentioned velocity range, I have filtered out the HVC from the background.

Now that I have filtered out my cloud from the background, the analysis area needs to be further narrowed

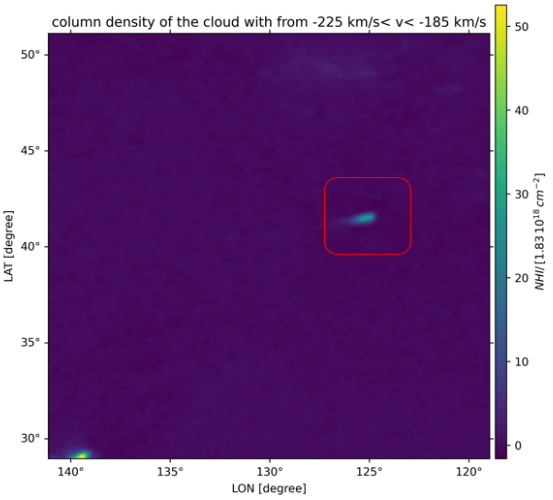

FIG. 8: Integrated column density map from -185< v <-225 km/s

down to a small rectangle around the HVC to visualize it properly.As the object area has been narrowed, it's important to have a clean set of data, so that our analysis is not affected by any unwanted noise. To achieve that I made a mask locating all the pixels with a value smaller than $10 \times dv \times \sigma_{rms} = 0.516K$ with $\sigma_{rms} = 0.043K$ (sensitivity of radio telescope, HI4PI Survey).[1]

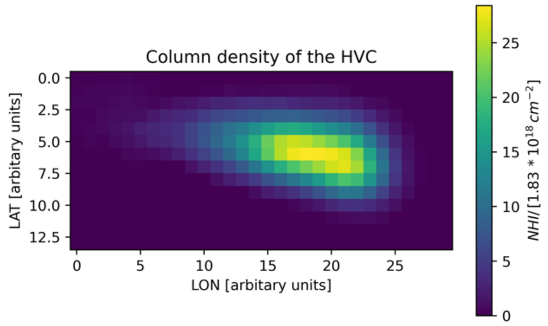

FIG. 9: Clean zoomed in view of the HVC which appears to have comet like shape

Since the exact size of the cloud is not known, I first studied the values of T_b after taking the average at each speed. Plotting the average values gives a curve, which despite looking like a Gaussian, shows an asymmetrical behavior. To extract the parameters of the curve I fitted it using a double Gaussian over the averaged data. The results of the fitting are shown in the same plot. Several remarks can be made here:

- First of all, the presence of two Gaussian distributions hints about two different parts of the cloud living along with each other, and moving towards us with slightly different velocities which perfectly follows Wolfire's analysis.[7]
- Considering that for higher temperatures we expect a wider distribution of the kinetic energy for the particles inside the cloud (and thus, a larger standard deviation), I can assume that both functions correspond to different shells of the cloud, a hot and warm one, whose sigmas are respectively 7.110 and 2.495km/s.

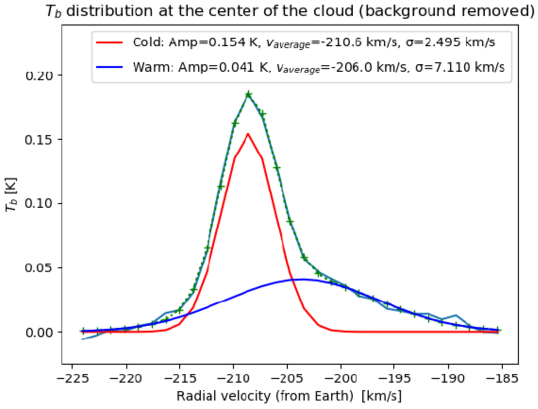

FIG. 10: Gaussian Curves for two different temperatures

Now that there is a general description of the area for the spatially averaged spectrum, I am interested in finding the values for each of the pixels, as it would allow me to find the real extension of each shell, and as well separate both of them. To do that, I started fitting from the very center of the cloud, using as initial parameters found for the average. Then, I jumped to the immediate neighbor to the left of it and fitted using as initial parameters the ones obtained for the previous pixel. The process was repeated until reaching the edge, and then it was again started from the center, but one pixel higher. The process was repeated until you reach the other corner. Once the fitting values for each of the pixels were obtained, and remembering that the area under a Gaussian (from $-\infty$ to $+\infty$) depends only on its standard deviation and amplitude, the contributions to the column density of each cloud can be calculated.

This way, we define a column density from the fitting given by :

$$\frac{\langle N_{HI} \rangle}{cm^{-2}} = 1.822 \times 10^{18} \times \sqrt{2\pi\sigma} \times Ad\left(\frac{v}{km.s^{-1}}\right) \quad (2)$$

Where σ and A are, respectively, the standard deviation and the amplitude of each Gaussian. Using the values obtained for the hot and warm cloud separately, we can simulate the column density of each shell.

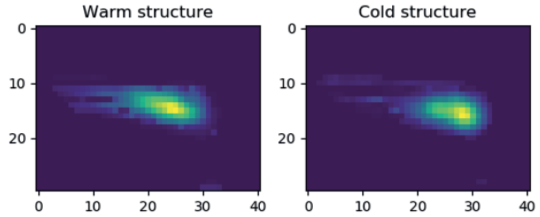

FIG. 11: Column density from two different temperatures shows the two phase structure: warm and cold

A. The two phase structure

From these plots, one can easily see that the cold structure is more dominant around the head region, whereas the warm structure is found to be prevailing near the tail region. Not only that but a shell-like structure can be appreciated, having the cold and hot phases separated.

The hot galactic corona provides the necessary pressure for the two-phase structure to exist in the cloud. This stable two-phase structure exists over a range of heights, but only within a narrow range pressure at each height.

Now that the HVC itself has been generally characterized, would like to estimate the distance at which it is located from us. To evaluate the distance, we will be assuming virial equilibrium between the shells of the gas. So, using the equation,

$$\frac{P_s}{k} = \underbrace{\frac{\langle N_{HI}\rangle \, T_k}{d\,\theta}}_{\text{kinetic pressure}} - \underbrace{\frac{\mu^2 \, G \, \pi \, \langle N_{HI}\rangle^2}{15\,k}}_{\text{gravitational pressure}} K.cm^{-3} \qquad (3)$$

Which describes the thermal pressure at equilibrium relative to the Boltzmann constant k, for a gas kinetic temperature T_k of a cloud located at a distance d and with angular diameter θ, where G is the gravitational constant and μ is the mean mass particle within the sphere.[7]

However, we can estimate the same pressure using the equation proposed by Wolfire(1995) based on equilibrium of the outer shell and the interstellar medium :

$$\frac{P_s}{k} = 2250 \times T_6^{0.5}(1.0 + \frac{z^2}{19.6})^{\frac{1.35}{T_6}} K.cm^{-3} \qquad (4)$$

where z is the vertical height over the galactic plane $z = dsin(L(latitude))$, and T_6 a parameter between 0.5 and 2.0.

Assuming that both expressions describe the pressure in the cloud well enough, we can determine the distance of the HVC by solving these two expressions, i.e. by equating the two pressure equations for the distance, for a particular T_6 value.

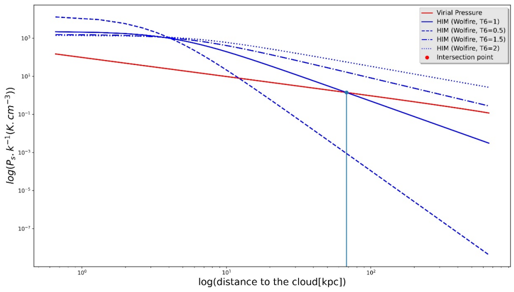

FIG. 12: Distance (cloud-observer) dependence of the external cloud pressure, as estimated from the Virial Theorem the function proposed by Wolfire[7] for different values of T_6.

IV. RESULT AND CONCLUSION

The distance to the cloud comes out to be 67.84 kpc for $T_6 = 1$. Hence a primordial origin can be ruled out since a two-phase structure exists only for z<2 kpc. Our cloud could be extragalactic in origin as the result of gas being stripped from the Large Magellanic Cloud(LMC) as supported by our calculated distance. The other important parameters of this cloud can be summarised as:

Property	Values
Distance to cloud	67.84 Kpc
Velocity of cold Phase	206 km/s
Velocity of warm Phase	210 km/s
Average Radius	848 pc
Virial Parameter (α)	0.0006513
Free fall time	105.69 Myr

FIG. 13: General properties of the HVC

Given the high column density and a gravitationally bound system, this particular cloud could likely form stars in the future.

V. MY THOUGHTS AND FUTURE WORK

I would be personally interested in studying the exact reason behind their high-velocity widths, especially the theory of Intermediate Mass Black Holes (IMBH) plunging these clouds (Takekawa et al). For this, I would need to compare the kinetic energies of many such clouds and try to relate that with the current theories which also include the supernovae explosion causing such high widths.

I would also like to study the metallicity and effect of magnetic fields on these clouds. Metallicity can tell us a great deal about their possible origin with more certainty. Nonetheless, there is indeed a lot going on with these clouds. Future analysis of the same would help us in understanding a lot of the unanswered questions.

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